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Iowa State University

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A hydrogeologic investigation of Ada Hayden Lake in Ames, Iowa

by

Evan Gary Christianson

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Co-majors: Geology; Environmental Science

Program of Study Committee:
William W. Simpkins, Major Professor
Chris Harding
Michael R. Burkart

Iowa State University

Ames, Iowa

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ABSTRACT

Ada Hayden Lake, a 49.6 ha, gravel-pit lake containing 5.2 million m^3 of water, comprises the emergency water supply for Ames, Iowa. This study characterized and quantified groundwater/lake interaction for the assessment of water supply potential. Hydraulic head, $\delta^{18}O$, $\delta^{2}H$, and ^{3}H data collected from 23 piezometers show that Ada Hayden Lake is a flow-through lake. Geochemistry is characterized by high P concentrations (SRP=93.6 μg/L), denitrification, and methanogenesis. A 3-D, finite-difference groundwater flow model shows that groundwater contributes 85 percent of the lake's water budget and approximately 42 percent of the soluble reactive P load. Model-simulated pumping of 10^6 gal/d from the lake during drought induces flow from the South Skunk River and lowers lake stage 3.6 m after 30 days. Pumping 1000 gpm in the aquifer for a year produces a drawdown of 3.75 m, induces flow from the lake, and lowers lake stage about 0.09 m.

INTRODUCTION

Mining or quarrying of rock or sand and gravel, where done in areas where the water table is close to the surface, often produces a pit lake. In regions where surface water bodies are scarce, these pit lakes are often used for recreation and water supply. Ada Hayden Heritage Park located on the north end of Ames, Iowa, at the site of the former Hallett's Quarry (T. 84 N., R. 24 W., Sec. 22, Story County), has as its centerpiece a gravel-pit lake, referred to in this study as Ada Hayden Lake (Figure 1). The City of Ames relies on Ada Hayden Lake as an emergency water supply. Water from the lake is pumped into the nearby South Skunk River to augment streamflow during dry periods. This process recharges the Ames aquifer and helps to maintain an adequate elevation of the potentiometric surface in the Downtown well field.

The population of Ames has grown steadily during the past 50 years, placing an increased demand on groundwater supplies. This growth, along with the increased use of the Ames aquifer for ethanol production, has caused some concern among residents and city leaders. As part of a reassessment of water supply for Ames, this study was conducted to examine the reliability of Ada Hayden Lake for emergency supply in the future. Understanding the groundwater flow system and its interaction with the lake, as well as the nutrient input from groundwater, is essential to understanding the limits to which the lake can be used as an emergency supply.

PURPOSE AND SCOPE OF RESEARCH

The purpose of this study was to characterize and quantify the groundwater-lake interaction for Ada Hayden Lake. Because the lake is so important to the community in terms of water supply, esthetics, and recreation, understanding the complete hydrologic picture is valuable. Depending on the geographic and geologic setting, along with the basin geometry, the groundwater component of a lake water budget can range from nearly 0 percent to nearly 100 percent. Ignoring the groundwater component of a lake could lead to erroneous lake management decisions affecting water supply and water quality.

The objectives of this study were to: 1) characterize the hydrogeology and groundwater flow to the lake; 2) characterize groundwater geochemistry in order to quantify nutrient input via groundwater; and 3) calculate a lake water-budget to assess the impacts of pumping the lake for water supply and the placement of new well field at Ada Hayden Park.

DESCRIPTION OF STUDY AREA

Ada Hayden Lake and Watershed

Ada Hayden Lake is located on the north end of Ames, Iowa, within the floodplain of the South Skunk River (Figure 1). The lake is composed of two basins, referred to here as the north and south basins. The total lake surface area is 49.6 ha (122.5 acres) with the north basin comprising 16.0 ha (39.5 acres) and the south basin 33.6 ha (83.0 acres). Both basins are relatively deep with steep sides and flat bottoms (Figure 2). The north basin has a maximum depth of 14.6 m (47.9 ft) and a mean depth of 7.3 m (24.0 ft). The south basin has a maximum depth of 18.6 m (61.0 ft) and a mean depth of 10.4 m (34.1 ft)(Downing, 2006). The two basins combined contain 5.2 million m^3 (1.4×10^9 gal) of water with the north basin containing 1.9 million m^3 (5.0×10^8 gal) and the south basin 3.3 million m^3 (8.7×10^8 gal)(Downing, 2006).

The watershed for Ada Hayden Lake is 997 ha (2,464 acres) with two predominate terrains (Figure 3). The Wisconsinan till in the uplands (Dows Formation) is characterized by hummocky, or swell-swale topography, with elongated ridge forms of moderate to high relief (3 to >8 m; 10 to >26 ft)(Quade et al., 2001). The lowlands, near the lake, are low-relief, modern floodplain of the South Skunk River. Maximum relief in the watershed is approximately 27 m (89 ft) with a maximum elevation of 302 m (990 ft) in the far northern part of the watershed and minimum elevation of approximately 273 m (896 to 897 ft) at Ada Hayden Lake.

Land use within the watershed for Ada Hayden Lake is primarily a mix of agricultural (45%), residential (24%), park land (14%), and golf course (7%)(Figure 4). Three unnamed tributaries drain into Ada Hayden Lake. The northern tributary has a watershed area of 539 ha (1,331 acres) and drains mostly agricultural land (70%), park/grassland (13%), and golf course (12%). The central tributary has the smallest watershed of the three tributaries at 155 ha (384 acres) and drains mostly agricultural (42%) and residential (43%) land. The southern tributary has a watershed of 183 ha (454 acres) and drains mostly residential land (92%).

Hydrogeologic Setting

Surficial Deposits

Surficial deposits in the uplands consist of late Wisconsinan till of the Dows Formation, deposited by the Des Moines Lobe of the last glacial advance 12,500 to 14,000 years ago (Figure 5; Prior, 1991). The ice margin reached its terminal position about 13,800 years ago near Des Moines (Bettis et al., 1996). The lobe advanced again 13,500 years ago, terminating at the Altamont ice margin located just north of the watershed for Ada Hayden Lake (Bettis et al., 1996). Sediments consist of fractured, silty loam to sandy loam, diamicton (till)(Quade et al., 2001). Till of the Dows Formation generally ranges in thickness from 15 to 20 m (49 to 66 ft). However, in some areas near Ada Hayden Lake, the thickness of the till is much less, or even absent, such as in the South Skunk River valley. Wisconsinan outwash that occurs in the valleys of the South Skunk River and Squaw Creek and terrace deposits along valley sidewalls are part of the Noah Creek Formation. Loess of the Peoria Formation (Wisconsinan) and undifferentiated Pre-Illinoian till and outwash also occur in the subsurface (Figure 5; Prior, 1991), particularly beneath the Squaw Creek floodplain on the east side of the Iowa State University campus (Wille, 1984).

South Skunk River

The South Skunk River (USGS HUC 07080105) exerts a major control on groundwater flow in the Ames area. Near Ada Hayden Lake the river has a bank-full width of approximately 7.6 to 22.9 m (25 to 75 ft) and a depth of 0.6 to 1.2 m (2 to 4 ft). In most reaches the river is gaining and acts as a groundwater discharge point. In other reaches the river is losing, recharging groundwater. Analytic element modeling suggests that the segment of the South Skunk River just south of Ada Hayden Lake is a losing stream (Simpkins and Christianson, 2007). Akhavi (1970) showed that pumping from the Downtown well field also induces infiltration from the South Skunk River. Analytic element modeling also suggests that groundwater exhibits an underflow, or flow parallel, relationship with the river south of Ames (Simpkins and Christianson, 2007).

The floodplain of the South Skunk River consists of 1.5 to 3.0 m (4.9 to 9.8 ft) of silty alluvium with some colluvial deposits along the valley walls. (Sendlein and Dougal, 1968; Quade et al., 2001). Outwash terraces along valley walls are composed of less than 5 m (16.4 ft) of coarse sand and gravel. Northeast of Ada Hayden Lake, many of the terraces directly overlie bedrock. Outwash terraces south of the lake generally overlie till of the Dows Formation (Quade et al., 2001).

Bedrock Stratigraphy and Topography

The bedrock stratigraphy in the Ames area consists of Mississippian carbonates and shales overlain unconformably by Pennsylvanian shales and sandstone (Figure 6). The Mississippian rock units present in the study area (from oldest to youngest) are the Maynes Creek (Hampton), Gilmore City, Burlington, Keokuk, Warsaw, and the St. Louis Formations.

Pennsylvanian rocks in the study area are generally undifferentiated, although they are most likely Des Moinesian Series within the Cherokee Group (Lemish et al., 1981).

The bedrock topography of the Ames area is characterized by bedrock valleys (or channels) incised into the Mississippian and Pennsylvanian units (Backsen, 1963; Kent, 1969; Palmquist et al., 1974; Schoell, 1967; Sendlein and Dougal, 1968) In Iowa, these are generally termed buried valleys and often contain buried-valley aquifers (Prior, 1991). Three principal bedrock valleys in the Ames area have been identified – the Jordan, Squaw Creek, and Skunk (Twenter and Coble, 1965; Palmquist et al., 1974). The Squaw Creek bedrock valley is the largest and most deeply incised of the three (Figure 7) and likely was the predominant drainage way during pre-glacial times (Wille, 1984).

Most important to the hydrogeology of Ada Hayden Lake is the Skunk bedrock valley (Figure 7). North of Ada Hayden Lake the axis of this bedrock valley runs from the northeast, near Peterson Pits (another set of gravel-pit lakes), to the south-southwest towards Ada Hayden Lake. South of the lake the axis of the valley trends southward and parallels the modern South Skunk River. Eventually, it turns towards the west, trending under downtown Ames and toward the Squaw Creek bedrock valley.

The Skunk bedrock valley is incised about 30 m (98 ft) into the bedrock and is filled with coarse sand and gravel outwash (Pre-Illinoian and/or Wisconsinan), with some loess and Pre-Illinoian till in the deepest parts. In previous work, Pre-Illinoian till was termed Nebraskan (Foster, 1969) or Kansan (Bible and Palmquist, 1973). Those terms are no longer in use and Pre-Illinoian will be used in this study. Sendlein and Dougal (1968) noted that two general trends are present for the outwash units; grain size increases with depth (a fining upward sequence) and decreases to the north. In the Ames area, cobbles up to 1 ft in diameter have been noted near the base of the outwash units (Sendlein and Dougal, 1968). Further discussion of the outwash units and the Skunk bedrock valley can be found in the results section.

Several faults have been identified in the Ames area (Figure 8). Although originally recognized as an anticline (Beyer, 1897; Zimmerman and Thomas, 1952), this series of faults was reinterpreted as a horst structure by Burch (1977). The history of the fault formation is not well known but is believed to be associated with one of several tectonic episodes of the late Paleozoic (Lemish et al., 1981; Wille, 1984). The orientation of the faults seems to be associated with older faulting from the formation of the Precambrian Midcontinent Rift System (about 1.1 billion years ago) that stretches from Lake Superior through Minnesota, Iowa, Nebraska, and Kansas (Ocola and Meyer, 1973; Burch, 1977). The apparent rejuvenation of Proterozoic faulting from the Midcontinent Rift has also been observed in Paleozoic sedimentary rock of Minnesota (Mossler, 2006).

Burch (1977) offered the most extensive interpretation of faulting in the Ames area and presented direct evidence of faulting in the form of slickenslides seen in core drilled in downtown Ames. Investigations at the Martin Marietta underground mine northeast of Ada Hayden Lake suggest faulting is present on the west side of their mine trending parallel to the South Skunk River (R. Martin, verbal communication, 2007). Wille (1984) suggested that the total offset of the faults ranges from 15 to 46 m (50 to 150 ft). About 10 m (30 ft) of displacement has been noted in the Gilmore City Formation on the west side of the horst at Martin Marietta mine (R. Martin, verbal communication, 2007). Exploration drilling for the proposed Ames Reservoir along the northern most fault near Peterson Pits shows an offset of 24.4 m (80 ft)(Sendlein and Dougal, 1968).

The exact location of the faults in the Ames area is not well known and open to some interpretation (Figure 8). Wille (1984) was the latest researcher to map the faults in the Ames area. Review of his work shows inconsistencies in the location of the faults. He presents two maps with fault information (p. 32 and 49 in Wille, 1984). There is a noticeable difference in the location of the northernmost fault, which could potentially underlie Ada Hayden Lake.

PREVIOUS WORK

Ames Aquifer and Ada Hayden Lake

Background

The Ames aquifer has been extensively studied since the 1960s, mostly through City of Ames-funded studies by students and faculty at Iowa State University. Backsen (1963) first defined the aquifer as all sand and gravel units that are hydraulically connected with the outwash unit of the Downtown well field (Skunk bedrock valley). By this definition, the Ames aquifer comprises a hydrostratigraphic unit including Pre-Illinoian and Wisconsinan outwash and modern alluvial deposits of the Squaw Creek and South Skunk River. Later studies by Akhavi (1970), Dougal et al. (1971), Burch (1977), Austin et al. (1984), and Wille (1984), provided additional information on the extent and hydraulics of the aquifer. Ver Steeg (1968), Yazicigl (1977), Drustrup (1982), and Maroney (1985) simulated groundwater flow in the aquifer using the electrical analog and USGS finite-difference models (MODFLOW and its predecessor).

Sendlein and Dougal (1968) showed that Ada Hayden Lake, Peterson Pits, outwash deposits, and the South Skunk River are hydraulically connected. Drawdown and recovery data for a series of wells installed in the outwash of the Skunk bedrock valley were analyzed during the dewatering of Peterson Pits (Figure 9). Results showed that all the wells experienced water level declines as a result of the dewatering. Based on these data and applying the modified non-equilibrium drawdown method of Ferris et al. (1962), they estimated the hydraulic conductivity (K) in the confined sand and gravel aquifer north of Ada Hayden Lake could range from 81.6 to 224.4 m/d (268 to 737 ft/d).

Emergency Water Supply

Water from Ada Hayden Lake (referred to as Hallett's Quarry prior to 2004) has been used several times in the past as an emergency water supply during times of drought. Water is pumped from the lake to the nearby South Skunk River to augment stream flow. As a result of pumping by the City of Ames' municipal wells, some reaches of the South Skunk River near Ames are losing; hence, water leaves the river and recharges the Ames aquifer (Akhavi, 1970; Simpkins and Christianson, 2007). The mean discharge for the South Skunk River from 1921 to 2006 at USGS gaging station 05470000, near Ada Hayden Lake, (Figure 10) was 4.9 cms (174.6 cfs)(USGS, 2007). However, during drought years the discharge can be very small or even dry up completely. It is during these low discharge periods that water from Ada Hayden Lake is needed to augment the stream flow in the South Skunk River and maintain the connection between the river and the Ames aquifer. Without this connection, water levels in the Downtown well field can drop dangerously low, thus severely reducing the production capacity of the aquifer.

Streamflow augmentation from the lake was first used during the drought of 1976-77. During the period of July 1976 to June 1977, the Ames area received only 30.86 cm (12.15 in) of precipitation – 50.8 cm (20 in) below normal (IEM, 2007). Throughout the winter of 1976, both the South Skunk River and Squaw Creek were dry and remained that way into the spring and early summer of 1976 (Seidel, 1990). The potentiometric surface in the Downtown well field declined 2.4 to 3.7 m (8 to 12 ft) from previous measurements done by

Akhavi (1970). This allowed the confined aquifer in the Downtown well field to convert to an unconfined aquifer (Burch and Wehrman, 1977).

Akhavi (1970) discussed the hydraulic connection between the South Skunk River and the Downtown well field. In the area just north of 13th Street (River Valley Park) the Skunk bedrock valley leaves its trend parallel to the South Skunk River and trends towards downtown Ames. He demonstrated that under pumping conditions, induced infiltration occurs in this stretch of the river and recharges the aquifer near the Downtown well field.

In 1977, Dr. Merwin Dougal from Iowa State University proposed to build a temporary low-head dam in the South Skunk River (north of 13th Street) to pool water; this would increase recharge to the aquifer in the Downtown well field and raise the water level (i.e., potentiometric surface) there. On July 11, 1977, construction began on a 2.4 to 3.0 m (8 to 10 ft) high dam composed of sand and gravel bulldozed from the riverbed and covered with a plastic liner on its upstream side (Seidel, 1990). On July 12, 1977 water was pumped from the south pit at Hallett’s Quarry (it contained three separate pits, or lakes, at the time) through a box culvert under U.S. Highway 69 and to the South Skunk River (Figure 11). According to records kept by the city, an average of 22,712 m^3/d (6 million gal/d) was pumped from the lake during a 28-day period. About 25 percent of the water pumped from the lake was lost either to infiltration into the alluvial sediments of the South Skunk River or evaporated along the approximately 4.0 km (2.5 mile) stretch of river prior to reaching the dam (Seidel, 1990). Water levels in the south pit dropped 1.05 m (3.45 ft) after one week of pumping. This was much faster than expected because water levels in the other two pits showed almost no response. The water levels (potentiometric surface) in the Downtown well field began to rise within a few days due to the rise in stage on the South Skunk River at the low-head dam. On

August 8th, 1977, 7.44 cm (2.93 in) of rain fell in Ames and heavy rain continued through August and into the fall, thus ending the drought and the need for Hallett's Quarry to be used to augment stream flow (Seidel, 1990).

Droughts in succeeding years caused water levels in the Downtown well field to drop to dangerously low levels and stream flow augmentation was again implemented. Water was pumped from Hallett's Quarry again during the drought of 1981-82. A permanent dam was constructed during the winter of 1983-84 and water was pumped from the quarry during the drought of 1988. During the summer of 2000 the water from Hallett's Quarry was once again needed for emergency supply. However, because the owners were attempting to sell the land, water from quarry was unavailable. Instead, water was pumped from Peterson Pits, located approximately 3.2 km (2 mi) upstream from the quarry. This experiment was largely unsuccessful and Peterson Pits were pumped dry in less than three weeks.

Even before the transition of ownership of Hallett's Quarry in 2000, the City of Ames recognized that water from the lake was a vital asset and that maintenance of excellent water quality was also necessary. In the early 1980s, the city commissioned the Iowa State Water Resources Research Institute (ISWRRI) to investigate the water supply alternatives for the city. A major component of that project was a study of Ada Hayden Lake. Antosch (1982) found that surface runoff, especially from the northern tributary, was contributing large amounts of sediment, nutrients (P and N), and fecal coliform to the three unconnected basins that existed at the time. To guide the city in managing the watershed to maintain excellent water quality, multiple scenarios for future land use, lake configuration, and diversion of surface runoff were simulated using the Canfield and Bachmann (1981) lake model. Antosch (1982) recommended that in order to reduce nutrient inputs, surface runoff be either detained in the form of wetlands or a reservoir near the lake, or diverted around the lake to the South Skunk River.

In 1996, when gravel mining operations ended, Hallett Materials Company began looking for potential buyers for the land surrounding the lake. Because of development interests, it became apparent that action by the city was necessary to acquire water rights to the lake and take steps towards maintaining good water quality. Simpkins and Christianson (2005) summarized the events leading to the City of Ames' acquisition of water rights and obtaining all the land surrounding the lake:

> *Summer 1998 – Des Moines developer approaches Hallett Materials Co. for purchase option and agrees to buy land. Ames' access to the quarry for water supply is denied.*
>
> *February 1999 – Des Moines developer approaches City of Ames about land annexation and development of a 1400-unit "Grand Lakes" subdivision.*
>
> *March to December 1999 - City examines proposal and hires lake consultant to report by April 2000.*
>
> *May 2000 – Consultant reports that water quality in the lakes will likely deteriorate over time, particularly with 1400 homes near the shoreline.*
>
> *June 2000 - Dry conditions cause water levels to drop in the Downtown well field, but access to lake water is not possible.*
>
> *Late Summer 2000 – City rejects developer proposal and decides to investigate purchasing the land for a park.*
>
> *September-October 2000 – About 6×10^5 m^3 of water is pumped into the South Skunk River from the lake at Peterson Pits; the pits were pumped dry after 491.5 hours (~ 20 days).*
>
> *November 2001 – Ames residents approve (86%) a bond issue to purchase the lake area.*
>
> *August 28th, 2004 – Ada Hayden Heritage Park is officially dedicated.*

In 2000, the City of Ames commissioned a study by Bonestroo, Rosene, Anderlik, & Associates (BRAA) to assess how best to protect the lake water quality (BRAA, 2000). The study used three empirical lake models to estimate and predict the total phosphorus concentration in the lake: the Canfield and Bachmann (1981) natural lake model, the Reckhow (1979) natural lake model, and the Vollenweider (1975) general lake model.

The BRAA study concluded that water quality could be maintained by building multi-cell constructed wetlands, or retention basins, on the three tributary streams just prior to their discharge into the lake (Figure 10); these were then constructed by the city. Such wetlands, when designed and constructed properly, have been shown to remove 40 to 80 percent of the total phosphorus, 20 to 80 percent of the nitrogen, and 80 to 100 percent of the suspended solids (Walker, 1987). The northern wetland complex has 4 cells and a large intermittent wetland area (Figure 10). However, because of an apparent design error, the intermittent wetland fills beyond capacity, flooding the northwest part of the park and preventing water from the northern tributary from entering the lake. As a result, most of the water from the northern wetland either evaporates or recharges the aquifer beneath it – that water then flows to the lake as groundwater. The implication of this situation will be discussed in a later section.

The main concern of the BRAA study was sources of phosphorus (P), which is generally the limiting nutrient in freshwater systems. Maintaining low P concentrations in surface water is the key to controlling water clarity, algae blooms, and oxygen levels. Contributions of P from groundwater are often ignored because concentrations are assumed to be small and the main source of P is assumed to be surface water.

Concentrations of P in groundwater may be large enough in some areas of Iowa to cause significant detrimental effects to surface water bodies and exceed EPA suggested nutrient criteria (Burkart et al., 2004; Carter et al., 2005). Burkart et al. (2004) found that the mean total dissolved P in groundwater, from four select areas in Iowa, representing five geologic materials (loess, loess derived alluvium, outwash, and fractured till), ranged from 74 μg/L to 212 μg/L. They concluded that in all areas of Iowa and the Midwest with intense agriculture it is likely that the shallow groundwater will have high concentrations of total dissolved P.

Groundwater may be a much larger source of P to lakes than is commonly thought, potentially increasing productivity in lakes. Brown (1986) showed that for seven lakes in east central Minnesota the groundwater component of the phosphorus load accounts for between 3 and 91 percent of the total P input to the lake. Work done by Shaw et al. (1990) on Narrow Lake in central Alberta showed that groundwater contributed 47 percent of the total phosphorus load to the lake, by far the largest single source of P. Brock et al. (1982) found that the mean concentration of P entering Lake Mendota in Wisconsin was 171.5 μg/L, accounting for 12 percent of the P load to the lake.

Given the potential importance of groundwater as a source of P to lakes in agriculturally productive areas, it is curious that the modeling done by BRAA (2000) for Ada Hayden Lake neglected the groundwater component of nutrient transport and the lake hydrologic budget. Antosch (1982) suggested that groundwater plays a significant role in the lake's nutrient budget, but he provided only rough estimates of the volume of groundwater entering the lake and determined the P concentration in groundwater (156 μg/L) from a limited number of samples.

Environmental Isotopes

Stable Isotopes

Environmental isotopes of hydrogen and oxygen have had a long history of use for groundwater studies (Freeze and Cherry, 1978). For the stable isotopes of hydrogen and oxygen, the most useful property is isotopic fractionation, which results from evaporation from an open water surface. It has been described as having two components (Craig and Gordon 1965; Froehlich et al., 2005). The first component of the isotope fractionation process from a water body is the fractionation of light and heavy water molecules in a relatively thin layer near the water surface due to differing saturation vapor pressures. Isotopically light water molecules have a higher saturation vapor pressure than isotopically heavy water molecules. So, at a given vapor pressure above the water surface there will be more isotopically light water molecules compared to isotopically heavy molecules.

The second component in the fractionation process from a surface water body is a kinetic process. This process is controlled by differing rates of water vapor diffusion from the thin, relatively turbulent-free, lower layer near the water surface to the turbulent layer above. The fractionation is a function of temperature, humidity, and the amount of turbulence, which is usually a result of wind. In general, more turbulence and lower humidity in the upper layer will allow for greater fractionation. The combined effect of the two fractionation processes leaves residual water enriched in ^{2}H and ^{18}O relative to ^{1}H and ^{16}O. This water will plot along an evaporation line of less slope than the meteoric water line (plot of $\delta^{18}O$ vs. $\delta^{2}H$). The slope of an evaporation line typically ranges from 2 to 6 (Clark and Fritz, 1997; Kehew, 2001).

Because the ^{2}H and ^{18}O signature of young groundwater is primarily controlled by mixing once it infiltrates into the ground, ^{2}H and ^{18}O can often be used as a tracer for groundwater recharging from a surface water body where extensive evaporation has occurred (Krabbenhoft et al, 1990; Stichler et al., 1999). Groundwater in temperate climates has an isotopic signature that is close to the weighted average of annual precipitation (Clark and Fritz, 1997). So, any deviations in the isotopic signature from the meteoric water line (plot of $\delta^{18}O$ vs. $\delta^{2}H$) indicate that the water has undergone a secondary fractionation after falling as precipitation. Often, groundwater down-gradient from a lake or wetland will show an isotopic signature that represents a mixture of precipitation and ^{2}H- and ^{18}O-enriched lake or wetland water (Krabbenhoft et al., 1990; Kehew et al., 1998; Froehlich et al., 2005). This groundwater will plot along an evaporation line with the degree of deviation from the meteoric water line being a function of both the amount to which the surface water body was enriched and the proportion of enriched, evaporated water to non-enriched water (Stichler et al., 1999).

Tritium

Tritium (^{3}H), a radioactive isotope of hydrogen, whose atmospheric concentrations rose due to above-ground hydrogen bomb testing, has been used extensively to date groundwater. Activities peaked during nuclear bomb testing of the 1950s and 1960s, and values of ^{3}H in precipitation reached a maximum of approximately 10,000 TU (tritium units) in 1963 (Mazor, 2004). Natural production of ^{3}H in the upper atmosphere introduces approximately 5 TU to precipitation each year (Mazor, 2004). A tritium unit equals one ^{3}H in 10^{18} hydrogen atoms (Freeze and Cherry, 1978) or 3.221 pCi/L (IAEA, 2001). Because ^{3}H has a relatively short half-life of 12.43 years, radioactive decay since the bomb peak has reduced activities to near background levels and ^3H is used mostly for relative age dating today. Groundwater that has little or no detectible ^3H is stated to be "old" or pre-bomb. Groundwater with detectable values of ^3H is stated to be "young" or post-bomb. A useful chart for interpretation of ^3H data in between those endpoint values is provided by Clark and Fritz (1997) for continental regimes:

<0.8 TU	Submodern – recharged prior to 1952
0.8 to ~4 TU	Mixture between submodern and recent recharge
5 to 15 TU	Modern (<5 to 10 yr)
15 to 30 TU	Some "bomb" ^3H present
>30 TU	Considerable component of recharge from the 1960s or 1970s
>50 TU	Dominantly 1960s recharge

Many of these ranges have shrunk due to decay during the past ten years since publication of the chart. In more common usage in the Midwest, ^3H activities less than 1 TU are generally considered as "pre-bomb." The present atmospheric input is not well known due to decommissioning of the Chicago, St. Louis, and Lincoln, NE recording stations in the mid-1990s. In 1992, the atmospheric ^3H input in Ames was 11.02 TU (Simpkins, 1995).

Groundwater-Lake Interaction

Interaction of groundwater and lakes has been studied since the early work of McBride and Pfannkuch (1975) and Winter (1976). Lakes can be primarily recharge lakes, discharge lakes, or flow-though lakes within the groundwater flow system (Winter et al., 1998). Most studies have shown an exponential decrease in groundwater discharge (seepage) with distance from the shoreline; hence, discharge is concentrated in the near-shore, shallow areas (McBride and Pfannkuch, 1975; Lee and Cherry, 1978; Pfannkuch and Winter, 1984). Most studies have been done on shallow "bowl-shaped" lakes and many of these concepts have not been applied to deep gravel-pit lakes. For lakes with geometries similar to Ada Hayden Lake potential exists for groundwater originating from longer, deeper flow paths to discharge into the lake further from shore. Discharge may also be more evenly distributed, or show a distribution pattern that deviates from the typical exponential decrease from the shoreline.

Several groundwater modeling approaches have commonly been used to simulate lake groundwater interaction. They include: cross-sectional, finite-difference models (e.g., Winter 1976); representing the lake as a "high K zone" by assigning high K and storativity values (e.g., Anderson el al., 2002); analytic element models that solve equations for surface water and groundwater conjunctively (e.g. Hunt and Krohelski, 1996; Simpkins, 2006); and 3-D finite-difference modeling (MODFLOW) using a LAK package (e.g., LAK1 – Cheng and Anderson, 1993; LAK2 – Council, 1998; LAK3 – Merritt and Konikow, 2000). Hunt (2003) argued that the LAK Package provides a sophisticated and superior method within MODFLOW. Results from analytic element modeling have been shown to produce comparable results to the LAK Package (Hunt, 2003).

Hunt (2003) noted that there are few publications that have applied the LAK Package in a groundwater model and attributed its limited use to lack of support by popular graphical user interfaces (GUIs), the complexity of discretization, and complex data requirements (Merritt and Konikow, 2000; Filby et al., 2002; Pint et al., 2003; Hunt, 2003). Other reasons for the lack of publications involving the LAK Package may include the necessity of using MODFLOW 2000 rather than the more familiar MODFLOW 96, the requirement to use the

SFR Package to simulate streamflow, and lag time necessary for GUIs to support the LAK Package.

The few studies that have been done involving the LAK Package show that it works very well and offers many advantages, including the ability to calculate lake stage independently, simulation of both steady-state and transient conditions (including the ability to pump water out of the lake), ability to account for streamflow, and documentation of the lake water budget (Hunt, 2003). Pint et al.(2003) noted that the ability for the LAK Package to calculate the lake stage independently, rather then specifying stage, is advantageous because it overcomes the problem of heads being overly specified in the immediate area of interest around the lake. Hunt (2003) suggested that a drawback of the LAK Package is the complex input that is required. However, this seems to have been overcome with the recent implementation into commonly used GUIs such as Groundwater Vistas.

METHODS

Seismic Refraction Survey

A seismic refraction survey was conducted on December 13, 2005 to better define the bedrock topography near the lake and to help define the stratigraphy for piezometer placement. The survey was supervised by Claire Hruby of the Iowa Geological Survey. The seismic refraction method measures the time for seismic waves to refract from a boundary between two stratigraphic layers with different seismic velocities (density). Using Snell's Law and the arrival times of the first refracted wave (head wave) along a string a geophones, the depths to the different boundaries can be calculated (Burger, 1992).

Three refraction lines were run on the north, northwest, and southwest sides of Ada Hayden Lake using an in-line spread of 24 geophones, spaced 5 m apart (Figure 10). A 4.5-kg (10 lb) sledge hammer, struck onto an aluminum coupling-plate, provided the seismic energy source. Shot points were located at -25 m, -5 m, 57.5 m, 120 m, and 145 m (geophone #1 was placed at 0 m; geophone #24 was placed at 115 m). A Geometrics StrataView® Exploration Seismograph recorded the signal from the geophones. To help reduce noise in the signal, the data were stacked a minimum of 25 times at shot points -25 m, -5 m, 120 m, and 145 m. A minimum of 10 stacks were recorded for the center shot point location (57.5 m). Data were processed and interpreted using SIPWIN® software by Rimrock Geophysics. First arrivals and layer assignments were picked manually and the SIPWIN® software calculated velocities and depths.

Piezometer Installation

Twenty-three piezometers were installed to map the water-table surface, obtain vertical hydraulic head data, provide groundwater sampling points, and determine the hydraulic relationship between the bedrock and the alluvial aquifers (Figure 10). Hollow-stem auger and mud-rotary drilling were used to install 16 piezometers in nests of three or four at five locations. Piezometers were constructed of 5.0 cm (2 in) diameter, schedule 40 PVC with 0.61 to 1.37 m (2.0 to 4.5 ft) screens (0.05 cm or 0.02 inch slot) and installed to depths ranging from 3.96 to 41.7 m (13 to 137 ft)(Table 1 and Appendix D). Stratigraphy was identified and logged at all sites during the piezometer installation (Appendices A to C). Continuous core was taken in plastic tubes at sites B and E to allow for more detailed description of the Quaternary sediments (see later section on sediment analysis and Appendices A to C).

Seven additional piezometers were installed by hand, both up-gradient and down-gradient of the lake, to provide data for a more accurate water-table map and additional water-quality sampling points. Of these seven piezometers, four (F5, F9, G16, H10) were constructed of 2.5 cm (1 in) diameter, schedule 40 PVC with 0.61 m (2.0 ft) screens (0.05 cm or 0.02 in slot) installed to depths ranging from 1.33 to 5.01 m (4.4 to 16.4 ft). Solinst™ model 615 drive points were used for the remaining three piezometers (I17, J8.5, J11) and were installed to depths ranging from 2.59 to 5.18 m (8.5 to 17.0 ft). A stilling well, constructed of 5.0 cm (2 in) diameter, schedule 40 PVC, was installed on the lake-outlet structure in the southeast corner of the lake. All piezometers were surveyed to an elevation accuracy of less than 1 cm using a GPS system by Mr. William Femrite, surveyor for the City of Ames. Piezometers were labeled using a combined letter-depth scheme. The letter represents the piezometer nest (Figure 10) and the number corresponds to the maximum depth (to the nearest foot) to the bottom of the piezometer screen. For example, B35 is located within piezometer nest B and was installed to a depth of about 35 feet. Details regarding piezometer construction are provided in drilling logs and well construction diagrams in Appendix C and D.

Sediment Analysis and Identification

Unlithified sediment and bedrock encountered during drilling for piezometer installation were analyzed and described to provide a more accurate and complete interpretation of the stratigraphy near Ada Hayden Lake. General descriptions of the cuttings and sediments were done on site during the drilling process. Particle-size analysis was conducted on sediment samples retrieved from cores collected at sites B and E. All coarse-grained samples were run using sieve separation and hydrometer analysis (ASTM Standard Methods D421-85 and D422-63) at the National Concrete Pavement Technology Center in the Department of Civil, Construction, and Environmental Engineering at Iowa State University. Sieve sizes used in the sieve separation were: 3 in, 2 in, 1.5 in, 1 in, 3/4 in, 3/8 in, No. 4 (4.75 mm), No. 10 (2.00 mm), No. 20 (850 µm), No. 40 (425 µm), No. 60 (250 µm), No. 100 (150 µm) and No. 200 (75 µm). All fine-grained (till and loess) samples were analyzed using a pipette and sieve method (Walter et al., 1978) at the Quaternary Laboratory in the Department of Geosciences at the University of Iowa. For the fine-grained sample analysis, all particles larger than 2.0 mm were removed and the remaining material was classified into sand (2.0 mm to 0.05 mm), coarse silt (0.05 mm to 0.02 mm), fine silt (0.02 mm to 0.0002 mm) and clay (<0.002 mm). To allow for comparisons among samples analyzed using different methods, percentages of sand, silt, and clay for the coarse-grained samples were calculated excluding the mass of the gravel portion. Representative cuttings of the bedrock obtained during piezometer installation from nests B, D, and E were sent to Dr. Brian Witzke of the Iowa Geological Survey for stratigraphic identification.

Hydraulic Conductivity (K)

Hydraulic conductivity (K) was estimated using falling-head and rising-head slug tests in piezometers at nests A, B, C, D, and E. To induce head displacement, a solid PVC slug, 2.5 cm (1.0 in) diameter, 1.52 m (5.0 ft) or 3.05 m (10.0 ft) long, was used**.** The length of the slug used in the test was determined based on the length of the static water column. Rapid water-level responses were recorded using a combination pressure transducer/data-logger (Instrumentation Northwest Inc. AquiStar® PT2X 0-15 PSIG Smart Sensor). The data-logger recorded at 0.1 second (10 Hz) intervals. Data from all but two piezometers were analyzed using the Bouwer and Rice (1976) method. Data from two piezometers showing an underdamped, or oscillatory, response were analyzed by the Springer and Gelhar (1991) method.

Groundwater Geochemistry

Water Quality

Groundwater in piezometers nests A, B, C, D, and E was sampled once a month from June 2006 to June 2007 for total phosphorus (total-P), soluble reactive phosphorus (SRP), ammonia-nitrogen (NH_3-N), nitrate-nitrogen (NO_3-N), total dissolved carbon (TDC), total organic carbon (DOC), total alkalinity, and pH (Appendix F). Piezometers were purged prior to sampling until the temperature and electrical conductivity stabilized. All samples were analyzed in the Limnology Laboratory in the Department of Ecology, Evolution, and Organismal Biology (EEOB) at Iowa State University. Total-P was analyzed using spectroscopy with a potassium persulfate digestion and conversion to molybdenum blue (standard method 4500-P A and E, Clesceri et al., 1998). The minimum detection limit (MDL) for total-P was 2 μg/L; the practical quantification limit (PQL) was 10 μg/L. Samples for SRP were filtered in the field through a 0.45 μm filter, placed in a glass bottle, and analyzed using spectroscopy with a potassium persulfate digestion and conversion to molybdenum blue (MDL 1 μg/L, PQL 5 μg/L; standard method 4500-P A and E, Clesceri et al., 1998). Ammonia-N was determined using the phenate method (MDL 16 μg/L, PQL 82 μg/L; standard method 4500-NH3 F, Clesceri et al., 1998). Nitrate-N was determined using second-derivative spectroscopy (MDL 120 μg/L; PQL 580 μg/L; Crumpton et al., 1992). Samples for TDC and TOC were analyzed using a Shimadzu TOC-V analyzer with TOC being measured as non-purgable organic carbon (NPOC)(MDL 1.12 mg/L, PQL 5.60 mg/L). All samples for total-P, SRP, NH_3-N, NO_3-N, TDC, and TOC were run in triplicate for quality assurance and quality control with the mean value presented here. Total alkalinity and pH were analyzed using titration and a pH meter. Total alkalinity is reported as mg/L $CaCO_3$ (MDL 2, PQL 10). Electrical conductivity, specific conductance (electrical conductivity adjusted to 25°C), and temperature (°C) were measured in the field using a YSI Model 30 meter. Dissolved O_2 was measured in the field using a CHEMetrics Oxygen 2 Single Analyte Meter (SAM) with CHEMetrics Vacu-vial™ ampoules (Gilbert et al., 1982).

Major Ions and Trace Metals

To characterize the geochemical environment of the aquifer, samples for anions (F, Cl, Br, NO_3, PO_4, SO_4) and total dissolved minerals (P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, Al, Na) were collected on August 3, 2006. Samples were analyzed at the University of Wisconsin-Madison, Soil and Plant Analysis Laboratory using Ion Chromatography (IC) for the anions and Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP-OES) for the total minerals. Samples for silica (SiO_2) analysis were collected on October 25, 2006 and analyzed at the Limnology Laboratory at Iowa State University using the Molybdosilicate Method (MDL 0.33 mg/L, PQL 1.64 mg/L; method 4500-SiO_2 C, Clesceri et al., 1998). Dissolved O_2 was measured in the field using a Hach Digital Titrator and an azide modification of the Winkler Method (method 8215; Hach Company, 2003).

Geochemical data were entered into the geochemical equilibrium model PHREEQC (Version 2.12.1-669; Parkhurst and Appelo, 1999) to calculate charge balances and saturation indices for select minerals. Saturation indices (*SI*) were calculated as:

$$SI = \log\left(\frac{IAP}{K_{eq}}\right)$$

where *IAP* is the ion activity product, and K_{eq} is the equilibrium constant. A negative SI value for a given mineral indicates that it is undersaturated, or that more of that given mineral could possibly dissolve in the groundwater. A positive SI value indicates that no more of a given mineral can dissolve and conditions may exist for that mineral to precipitate from the groundwater. A SI value of zero suggests the water is in geochemical equilibrium with respect to a mineral. Charge balance of anions and cations was below 10 percent for all samples. The maximum charge balance error was 5.67 percent (sample from piezometer D20)

Dissolved Gases

Samples for the dissolved gases methane (CH_4) and nitrous oxide (N_2O) were collected on November 21, 2006, from the 16 main piezometers around the perimeter of the lake. The purpose of these samples was to check for denitrification and redox conditions of the groundwater. The sampling method and analysis were similar to Simpkins and Parkin (1993). Samples were collected in 20 mL, glass vials, flushed with helium (He) gas, evacuated, and stoppered with a self-sealing septum. A syringe was used to fill the vials with 10 mL of groundwater leaving a 10 mL headspace. The head space was then adjusted to atmospheric pressure in the laboratory using He gas. Samples were shaken at room temperature to allow for the gas to partition into the head space, which was then analyzed using a gas chromatography (ECD and FID) at the National Soil Tilth Laboratory in Ames, IA. The Bunsen coefficient for CH_4 and N_2O was used to determine the dissolved gas concentration in the sample (Parkin and Simpkins, 1995).

Environmental Isotopes

Stable Isotopes

Samples for stable isotopes of hydrogen and oxygen were collected on August 30, 2006. All isotope results are presented in standard δ notation expressing deviations from Vienna Standard Mean Ocean Water (V-SMOW)

$$\delta_{sample}\,(‰) = \frac{(R_{sample} - R_{std})}{R_{std}} \times 1000$$

where:

R_{sample} is the ratio of $^{2}H/^{1}H$ or $^{18}O/^{16}O$ in the sample

R_{std} is the ratio in the international standard (V-SMOW).

Values of $\delta^{2}H$ were determined at the Environmental Isotope Laboratory (EIL) of the University of Waterloo, Canada, using manganese reduction and methods similar to Shenker et al. (2005). Values of $\delta^{18}O$ were determined at both the Stable Isotope Laboratory in the Department of Geological and Atmospheric Sciences at Iowa State University (ISU) and the EIL laboratory at the University of Waterloo. The analytical precision was ±0.8‰ for $\delta^{2}H$ and ±0.145‰ for $\delta^{18}O$. Because of discrepancies in the $\delta^{18}O$ values determined between the EIL and ISU laboratories, some of the ISU values were corrected to EIL laboratory equivalents to allow for comparison to previous studies by Simpkins (1995) and others in North America.

The $\delta^{2}H$ and $\delta^{18}O$ values were plotted to analyze for deviations from a local meteoric water line lending evidence to groundwater being recharged from an evaporative source (the lake or constructed wetland). Surface waters are often enriched in ^{2}H and ^{18}O in comparison to local precipitation. This enrichment is a result of isotopically lighter water molecules being selectively evaporated and leaving isotopically heavy molecules behind in the residual water (Froehlich et al., 2005).

Data collected for this study were plotted to determine a local meteoric water line (LMWL) and to look for trends in the isotopic signature of the groundwater around Ada Hayden Lake. Data points were grouped into two categories; those showing enriched $\delta^{18}O$

and δ^2H signatures originating from an evaporative source and those that showed a signature reflective of precipitation. Reduced major axis (Davis, 2002) and least squares regression analyses were used on data points reflective of precipitation to plot a LMWL (IAEA 1992; Bohonak, 2004; van der Linde, 2004). Reduced major axis and least squares regressions were also performed on data points from an evaporative source to obtain an evaporation line. Reduced major axis regression was applied because it is appropriate when both the X and Y variables have inherent error; it may be the more appropriate regression analysis for these data (Davis, 2002). However, because many authors during the past 30 years have applied least squares regression to present LMWLs, both approaches are presented in this study. Values were compared to those in Simpkins (1995), which established a LMWL for the Ames area. Hydraulic head and groundwater flow data from the nearest piezometer nests were used to confirm that water could be originating from the sources suggested by the isotope results (i.e., the lake and northern wetland complex).

For isotopic data from groundwater on the down-gradient, eastern side of the lake, a mixing ratio was used to estimate the percent of groundwater that originated from the lake. The isotopic composition of the lake and the background groundwater isotopic composition were used as end members.

$$\%\ LakeWater = \frac{\delta^{18}O_{sample} - \delta^{18}O_{gw}}{\delta^{18}O_{lake} - \delta^{18}O_{gw}}$$

(Clark and Fritz, 1997)

where: $\delta^{18}O_{sample}$ is the value in groundwater from the piezometer of interest, $\delta^{18}O_{lake}$ is the value of the lake water and $\delta^{18}O_{gw}$ is the value of the background groundwater. The mean value of all the groundwater samples falling along the LMWL was used as the background groundwater value.

Tritium

To estimate the relative age of groundwater, samples for enriched tritium (^3H) were collected from piezometers upgradient of the lake (A15, A35, A60, B13, B35 B64, B138, C15. C35, C70) and the deepest piezometer at nest E (E105) on the down-gradient side (Figure 10). Other piezometers on the down-gradient side of the lake were not sampled because stable isotope values had already indicated that the groundwater there was young and originated from the lake (see results section) Samples were analyzed at the EIL. Tritium samples were determined by direct scintillation counting after electrolytic enrichment. Detection limits were 0.8 TU and analytical precision for the 11 samples was ±0.5 TU.

Groundwater Model

A 3-D, finite-difference, groundwater flow model (MODFLOW-2000; Harbaugh et al., 2000) with the LAK and SFR packages was used to simulate the groundwater lake interaction. The objective of the modeling was to quantify the amount of water entering and exiting the lake via groundwater and calculate a nutrient budget for the lake. For the initial model, the groundwater flow system was assumed to be steady-state. The governing equation for the simulation under anisotropic and heterogeneous conditions is:

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) + W = 0$$

where: h is the hydraulic head (L); K_x and K_y, are the horizontal hydraulic conductivity values (L/T); K_z is the vertical hydraulic conductivity value (L/T); and W is the source/sink term (L/T). For the transient simulations, the governing equation for anistropic and heterogeneous conditions is:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)+W(x, y, z, t) = S_s \frac{\partial h}{\partial t}$$

where S_s is specific storage and t is time.

The LAK Package uses inactive cells within the model grid to represent a lake basin. Flow into the lake from an aquifer is based on Darcy's Law:

$$q = K \frac{h_l - h_a}{\Delta l}$$

where: q is specific discharge (L/T); K is the hydraulic conductivity of the materials between the lake and a location within the aquifer (L/T); h_l is the lake stage (L); h_a is the head within the aquifer (L); and Δl is the distance between h_l and h_a (L).

For application within MODFLOW the specific discharge is integrated over the cross-sectional area (A) of a grid cell allowing for a volumetric flux to be calculated.

$$Q = qA = \frac{KA}{\Delta l}(h_l - h_a) = c(h_l - h_a)$$

The quantity c is termed the conductance (L^2/T):

$$c = \frac{A}{\frac{b}{K_b} + \frac{\Delta l}{K_a}}$$

where: K_b is the hydraulic conductivity of the lake bed; K_a is the hydraulic conductivity of the aquifer; and b is the lakebed thickness (L).

A lake water budget accounting for all sources and sinks is used to calculate the lake stage.

$$h_l^n = h_l^{n-1} + \Delta t \frac{p - e + rnf - w - sp + Q_{si} - Q_{so}}{A_s}$$

where h_l^n and h_l^{n-1} are the lake stages from the present and previous time steps (L); Δt is the length of the time step (T); p is the precipitation rate over the lake (L^3/T); e is the evaporation rate from the lake surface (L^3/T); rnf is the surface runoff directly into the lake (L^3/T); w is the withdrawl or pumping from the lake (L^3/T); sp is the seepage between the lake and the aquifer; Q_{si} is the flow into the lake from streams; Q_{so} is the flow out of the lake from streams; and A_s is the surface area of the lake.

The terms Q_{so} and Q_{si} are supplied to the LAK Package from the Streamflow-Routing Package (SFR1, Prudic et al. 2004). The SFR1 Package calculates flow between the stream and the aquifer similar to the LAK Package using Darcy's Law. Instead of a lakebed thickness and K, a streambed thickness and K are defined to calculate the conductance. The advantage of the SFR1 Package is that it is able to rout flow from one stream cell to the next allowing for an estimate of baseflow within the stream. The flow at the last stream cell prior to entering the lake is read by the LAK Package as stream flow into the lake.

To understand the methods used in the construction and conceptualization of the model the reader must first be presented with the results from various other parts of this research. A full description of the model construction and calibration is presented in the Results and Discussion section.

Nutrient Budget

Nitrogen and phosphorus are the most important nutrients in controlling water quality in freshwater lakes (Kalff, 2002). Similar to most freshwater lakes, P is the limiting nutrient for

Ada Hayden Lake, with a N:P ratio of 33 (data from 2001-05; Downing, 2006). Controlling P is most often the focus of nutrient-control programs (Kalff, 2002) and has been the focus of previous studies to maintain excellent water quality in Ada Hayden Lake (Antosch, 1982; BRAA, 2000). More data are now available to fully quantify the amount of P entering the lake (i.e., the groundwater component has now been quantified). Nitrogen and silica, while important in controlling water quality for some systems (Kalff, 2002), are not major controlling nutrients for water quality in Ada Hayden Lake, due mostly to the high N:P ratio and relatively low levels of silica (Downing, 2006). Quantifying the load of P to Ada Hayden Lake is important to help manage water quality for lake recreation and water supply use.

The P load to the lake from groundwater was estimated using modeled groundwater discharge to the lake and measured SRP concentrations in groundwater. SRP was used instead of total-P because it is filtered and is generally a better representation of P transported by groundwater. Total-P is an unfiltered sample and will have a component consisting of colloidal P which may move only in large pore spaces and fractures. Annual surface water discharge and P load to the lake from the three tributary streams was estimated using a GIS-based curve number model, L-THIA (Long-Term Hydrologic Impact Assessment)(Engel, 2005), in conjunction with P export coefficients (Reckhow et al., 1980; Panuska and Kreider, 2003). A range of coefficients was used for each land use to account for uncertainty in the values (Table 2). Although data on P concentration of the water in streams was collected by Downing (2006), the data set was not complete enough for this analysis, nor did it properly represent the storm water component of stream flow. In that study, water samples from the streams were collected once a month, or less, depending on stream flow. Because most stream flow into the lake occurs during storm events, the P values are not representative of the load of P that actually reaches the lake. The storm flow component of the streams is also not represented in the steady-state MODFLOW model. The curve number model, L-THIA, performs a transient simulation that uses daily precipitation values. It can more accurately predict total inflow and P load to the lake from surface water.

Because the effectiveness of the wetlands, or retention basins, is unknown, two simulations were used to estimate the total P levels in the mixed lake. One simulation assumed that the wetlands remove zero P load from the streams. The other simulation assumed that the wetlands capture 50 percent of the total P in the streams, which is a typical value for constructed wetlands (Walker, 1987).

Phosphorus load to the lake directly from precipitation and dry fall was estimated to be 12.6 kg/yr (about 0.254 kg/ha/year for the Ames area; Anderson and Downing, 2006). To obtain a range of possible P loads to the lake from groundwater, the 10^{th} and 90^{th} percentiles and the arithmetic mean of all SRP values measured during the study period were used in conjunction with the modeled groundwater discharge to the lake.

The Wisconsin Lake Modeling Suite (WiLMS)(Panuska and Kreider, 2003) was used with the total estimated P load to select the appropriate empirical model to predict P concentration in the lake. The Canfield-Bachmann model for a natural lake consistently produced the best results (Canfield and Bachmann, 1981). First developed in Iowa, the Canfield-Bachmann model was tested on over 700 lakes worldwide and was shown to reliably predict the P concentration of lakes with a wide range of sizes, depths, flushing rates, and P loads (Canfield and Bachmann, 1981). The Canfield-Bachmann model uses the empirical relationship:

$$P = \frac{L}{z\left(0.162\left(\frac{L}{z}\right)^{0.458} + p\right)}$$

where:

P = the total phosphorus concentration of the lake water (mg/m^3)

L = the areal phosphorus load for the lake ($mg/m^2 \cdot yr$)

z = the lake mean depth (m),

p = the lake flushing rate (1/yr).

The Canfield-Bachmann model uses the concept of a sedimentation coefficient (σ) to account for phosphorus loss to the lakebed sediments. Canfield and Bachmann (1981) found that the phosphorus sedimentation coefficient was most strongly correlated with the lake mean depth (z) and the areal phosphorus load (L). The resulting equation for σ as determined by Canfield and Bachmann (1981) for a natural lake is:

$$\sigma = 0.162\left(\frac{L}{z}\right)^{0.458}$$

Given σ, the Canfield-Bachmann model could also be written as:

$$P = \frac{L}{z(\sigma + p)}$$

Canfield and Bachmann (1981) also found that σ is correlated to the total water input to a lake and the hydraulic flushing rate. The equation for σ above was developed because the mean depth and areal phosphorus load were most strongly correlated.

Areal phosphorus load was calculated by dividing the total P load for the lake by the lake surface area (496,023 m^2 for Ada Hayden Lake). Lake flushing rate was calculated by dividing the total water input (“hydraulic load”) by the lake volume (5,200,000 m^3 for Ada Hayden Lake). The flushing rate represents the number of lake volumes that are replaced each year by water inputs to the lake.

RESULTS AND DISCUSSION

Seismic Refraction Survey

Results from the seismic refraction survey are consistent with previous boring data and stratigraphy information collected at the site during this project. Two refractions were used to define three layers along each line (Figure 12). The uppermost unit (Layer 1) is approximately 5 m (16.4 ft) thick along each refraction line, but drilling showed no lithologic change at that depth (see sediment description section); hence, this layer was interpreted to be an unsaturated zone above the water table. A depth of 5 m (16.4 ft) to the water table is greater than that observed in piezometers. However, 5 m (16.4 ft) is also the minimum resolution for first refraction using a 5 m (16.4 ft) geophone spacing. Layer 2 was interpreted to be outwash based on an estimated seismic wave velocity of 1,391 m/s (4,564 ft/s) to 1,823 m/s (5,981 ft/s). Layer 3 was interpreted to be carbonate bedrock based on an estimated seismic wave velocities of 3,797 m/s (12,457 ft/s) to 5,031 m/s (15,506 ft/s) – values typical for carbonate rock (Kearey et al., 2002).

Depth to bedrock along the three seismic lines was 21 to 36 m (67 to 118 ft)(Figure 12). Line 1, north of the lake, shows the slope of the western sidewall of the Skunk bedrock valley. Depth to bedrock along Line 1 ranges from 25 m (82 ft) on the west end to 36 m (118 ft) on the east end. Depth to bedrock along Line 2, on the western side of the bedrock valley, ranges from 26 m (85 ft) at the north to 35 m (115 ft) in the central to southern part of the line. Drilling at the southern end of Line 2 (piezometer nest B) revealed bedrock at 35.5 m (117 ft), very close to the depth predicted by the seismic refraction. Depth to bedrock along Line 3, near the southwest side of the bedrock valley, ranged from 27 m (89 ft) on the west end to 30 m (98 ft) on the east end.

Depth to bedrock along Line 1 may be overestimated due to a classic "blind-layer" problem (Burger, 1992). Drilling logs near that location (Army Core of Engineers #8; Sendlein and Dougal, 1968) reveal till overlying sand and gravel. This stratigraphy does not satisfy the requirement that an underlying layer should possess a higher velocity than the layer above it for a head wave to be produced (Burger, 1992). However, depth to bedrock results from the seismic survey fit reasonably well with previous interpretations of the bedrock topography in this area, suggesting that the blind layer problem may be insignificant.

Wind-induced signal noise increased during the seismic survey. Mounding snow around the individual geophones helped to reduce noise; however, noise in the signal likely produced more error in lines 2 and 3. Line 1 showed the least noise and therefore the least error in estimating the depth to bedrock, assuming the blind layer problem is not significant. Line 3 showed the most noise and therefore the greatest error in estimating depth to bedrock.

Hydrogeology

Quaternary Geology

At least five Quaternary units, including two outwash units, have been recognized in this study. The Ames aquifer includes two outwash units: 1) the Noah Creek Formation of the Wisconsinan glaciation which is generally associated with the modern South Skunk River, and 2) an older (and deeper) Pre-Illinoian outwash unit, associated with the

Skunk bedrock valley (Figure 13). Based on similar elevations and materials, the Pre-Illinoian outwash at Ada Hayden Park may be stratigraphically equivalent to the outwash that forms the aquifer in the Downtown well field. Evaluation of drilling logs (Sendlein and Dougal, 1968; IGS, 2007) shows that where the Skunk bedrock valley diverges from the modern valley of the South Skunk River (north of Ada Hayden Lake and near the Downtown well field), outwash comprising the aquifer is confined by 15 to 30 m (49 to 98 ft) of late-Wisconsinan till (Dows Formation), another till unit, and loess (possibly Peoria loess; termed silt by Nicklin, 1974). Where the Skunk bedrock valley lies parallel to, or coincides with, the modern South Skunk River, the Wisconsinan outwash overlies the Pre-Illinoian outwash directly and together they form an unconfined aquifer.

Bedrock Lithology

Analyses of cuttings from boreholes B, D, and E by Dr. Brian Witzke at the Iowa Geological Survey indicate the ancestral South Skunk River cut through several bedrock units as it formed the Skunk bedrock valley (Figure 14; Table 3). Parts of these units were intersected during the course of drilling for piezometer nests. The bedrock units present at the top of the bedrock surface (subcrop) are dependent on the location within the bedrock valley. The oldest unit present in subcrop around Ada Hayden Lake is the Gilmore City Formation, which occurs near the center of the Skunk bedrock channel and is present as the first bedrock unit at piezometer nest B. The Burlington Formation subcrops at piezometer nest E, which lies more towards the bedrock valley wall. The Keokuk Formation is present in the bedrock subcrop at piezometer nest D, which is also on the bedrock valley wall where depth to bedrock is 9.1 m (30 ft).

Hydraulic Conductivity (K)

Values of K range from 8 x 10^{-9} m/s (2.3 x 10^{-3} ft/d) for till to 7 x 10^{-4} m/s (198 ft/d) for well-sorted coarse sand (Table 4) and lie within accepted values for those materials (Simpkins and Parkin, 1993; Simpkins, 2006). Underdamped, oscillatory responses were observed during tests in two wells, C70 and B64 – the former is screened in well-sorted coarse sand and the latter in coarse sand and gravel. All other slug tests, exhibited a normal, straight-line (overdamped) response.

Hydraulic conductivity values of the outwash, determined from slug tests as part of this study, are less than values for other areas of the Ames aquifer. The geometric mean of all outwash K values from this study was 2 x 10^{-4} m/s (56.7 ft/d); slightly more than an order of magnitude less than values found by previous researchers ranging from 1 x 10^{-2} m/s (2835 ft/d) to 8 x 10^{-3} m/s (2268 ft/d). (Akhavi, 1970; Wille, 1984; Maroney, 1994; Simpkins and Christianson, 2007). Outwash at Ada Hayden Lake may be more fine-grained or have a larger percentage of silt than in the more productive parts of the Ames aquifer previously studied. This interpretation is consistent with observations by Sendlein and Dougal (1968) that grain size in the Ames aquifer decreases to the north. Simpkins and Christianson (2007) noted that a smaller K value of 6.5 x 10^{-4} m/s (184 ft/d) was needed at Ada Hayden Lake for the lake level to calibrate in their regional groundwater flow model.

The discrepancy in K values for different parts of the Ames Aquifer may represent a scale effect. In general, estimates of K have been shown to increase with the scale of the test used to measure them (Bradbury and Muldoon, 1990; Rovey and Cherkauer, 1995;

Schulze-Makuch and Cherkauer, 1998). Previous K values from the Ames aquifer were obtained from pumping tests, which examine a much larger volume of material then slug tests used in the present study. Pumping tests may also be biased towards higher values by the very coarse and more productive parts of the aquifer used for municipal water supply.

Groundwater Flow

Hydraulic head data taken during the study (Appendix E) indicate that groundwater enters Ada Hayden Lake from the north, west, and southwest, and exits on the east and southeast sides. This relationship is shown by a water-table map produced from measurements taken on December 20, 2006 (Figure 15). The pattern of inflow and outflow is also supported by vertical hydraulic head gradients (Figure 16). An upward vertical gradient indicates groundwater flow up and into the lake at piezometer nests A and B. At nests D and E, downward vertical gradients indicate groundwater flow out of the lake. Hydraulic heads are nearly identical with depth at nest C, suggesting mainly horizontal flow towards the lake.

Changes in hydraulic head values over the study period generally mirrored changes in lake stage (Figure 17 and Appendix E). Comparison of the magnitude and direction of vertical head gradients between December 2006, a dry period, and May 2006, a very wet period, show little difference (Figure 16). This suggests that the groundwater flow field around the lake is not affected greatly by increased recharge or changes in lake stage.

Environmental Isotopes

Stable Isotopes

Groundwater at Ada Hayden Lake can be separated into two distinct groups based on isotopic composition: groundwater enriched in δ^2H and δ^{18}O, plotting along an evaporation line; and groundwater not enriched, plotting along a LMWL (Figure 18; Table 5). The δ^2H and δ^{18}O signature of non-enriched waters plots along a line similar to that of the global meteoric water line (Craig, 1961) and the LMWLs proposed by other researchers for Minnesota and Iowa (Simpkins, 1995; Tomer and Burkart, 2003; Cowdery, 2005; Gourcy, 2005; Schilling and Tassier-Surine, 2006). Using a least squares regression for the isotopic data in piezometers at Ada Hayden Lake and the City of Ames well fields yielded a LMWL of $\delta^2H = 7.24(\delta^{18}O) + 3.94$, nearly identical to the LMWL of Simpkins (1995) for the Ames area. Reduced major axis regression provided a LMWL of $\delta^2H = 8.34(\delta^{18}O) + 11.59$. The δ^2H and δ^{18}O signature of enriched water plots along an evaporation line (Figure 18). Least squares regression on the data points of this group yields an evaporation line of $\delta^2H = 5.16(\delta^{18}O) - 11.13$; reduced major axis regression yields a similar evaporation line of $\delta^2H = 5.25(\delta^{18}O) - 10.76$.

Groundwater from both piezometer nests D and E generally shows an enriched isotopic signature, suggesting that a large fraction originated from the lake. Isotopic data for groundwater from piezometers D20, D35 and D55, located near the southeast corner of the lake, plot along the evaporation line (Figure 18). These data corroborate the hydraulic head data, which show that water is exiting the lake at this point and flowing to the southeast towards the South Skunk River (Figure 15). Based on mixing ratio calculations, approximately 46.4 percent, 74.7 percent, and 54.3 percent of the groundwater in D20, D35, and D55, respectively, originates from the lake (Table 5).

Groundwater from the two piezometers at nest E (E22 and E53) also plots along the evaporation line (Figure 18). These data also corroborate the hydraulic head data. Groundwater from piezometer E22 shows the greatest enrichment of δ^2H and $\delta^{18}O$, and 100 percent of that water originates directly from the lake according the mixing ratio calculations (Table 5). This relationship suggests that no mixing of surface recharge or deeper groundwater occurs at a depth of 6.7 m (22 ft). Enriched groundwater at piezometer E22 may originate from shallow depths within the lake. Ada Hayden Lake is strongly stratified in the summer and little vertical mixing occurs (Downing, 2006). This allows surface water to become enriched in the late summer at the expense of deeper water. Thus, the enriched water in the upper stratified zone is flowing directly along a shallow flow path to piezometer E22. Because the lake was only sampled near the surface, however, these are estimates of lake water percentages, at best. The percentage originating from the lake may actually be much greater at nest D and at E53. Because the surface water is presumably more enriched than at depth and these values are used as end members in the mixing ratio, the percent of lake water in the deeper piezometers may be underestimated.

Groundwater from the deepest piezometer at nest E (E105) in limestone bedrock lacks evidence of an evaporative isotopic signature. This is consistent with the vertical hydraulic gradient, which shows hydraulic head to be less in E105 than in E53. Rather than indicating vertical movement of lake water downward to this point, it more likely suggests that there is a separate bedrock flow system that is confined by both the overlying till and loess (see Appendix A). In short, the isotopic data suggest that enriched water from the lake does not recharge the bedrock aquifer on the down-gradient side of the lake.

Groundwater samples from the two shallow piezometers at nest B (B13 and B35) on the northwest side of the lake also show an evaporative isotopic signature (Table 5). In contrast, the deeper piezometers there (B64 and B138) show an isotopic signature typical of most groundwater in the area, plotting along the LMWL. Hydraulic head data support the two distinct isotopic signatures (Figure 19). The hydraulic gradient between piezometers B13 and B35 was downward during most of the study period, indicating that isotopically enriched water from the wetland located directly west of nest B (Figure 10) is likely recharging the aquifer at that point. Groundwater in the deeper piezometers (B64 and B138) show an upward hydraulic gradient, indicating that water is flowing up towards the lake from the sand and gravel aquifer and bedrock.

The isotopic signature from piezometer B35 shows the least enrichment in δ^2H and $\delta^{18}O$ of all groundwater samples that plot along the evaporation line (Figure 18). There are two possible explanations. First, little water from the wetland may actually reach the screened interval of B35 and most of the water may flow directly to the lake along a shallower flow path. Second, the vertical hydraulic gradient at B35 is reversed and directed upward when the wetland is dry (Figure 19). The gradient reversal allows for a mixing of both enriched water recharging from the wetland complex (when the vertical gradient is downward) and water from a deeper source not enriched in δ^2H and $\delta^{18}O$ (when the vertical gradient is upward). The mixing of these two waters would allow for an isotopic signature intermediate in composition compared to the other samples. There is no indication of a isotopic depletion with depth at nest B and the signatures are similar to shallower non-enriched values, which simply suggests that there are no remnants of glacial meltwater in the system (Simpkins and Bradbury, 1992); i.e., groundwater age could be young.

Groundwater from piezometer nests A and C on the north and southwest sides of the lake, respectively, shows an isotopic signature typical of groundwater in the area plotting along the LMWL (Figure 18). Hydraulic head data shows that groundwater at nest A is flowing up and towards the lake (Figure 16). Predominantly horizontal flow occurs at site C, as indicated by hydraulic head relationships and the nearly identical values of stable isotopes with depth.

In summary, the stable isotope data collected in this study show that enriched lake water is flowing out of the lake on the east and south sides of the lake (Figure 20). These data also indicate that enriched water from the wetland is recharging the aquifer and flowing along a shallow flow path towards the lake. Groundwater at depth at nests B and E, and in nests on the north and southwest sides of the lake, has an isotopic signature of typical groundwater in the area.

Tritium

Enriched tritium analysis shows that most groundwater from the piezometers surrounding Ada Hayden Lake contain modern tritium (“submodern”) that entered the groundwater flow system less than 5 to 10 years ago (Table 5; Clark and Fritz, 1997). Simpkins (1995) showed that the tritium activity in precipitation in 1992 was 11.02 TU, which would have decayed to 5.02 TU in 2006, so the larger tritium values seen in groundwater at the lake suggest slightly older groundwater. Modern precipitation input values at the lake are unknown, however. If the evaporative isotopic signatures seen in groundwater at B13 and B35 indicate very recent recharge, then tritium values of 8.0 and 7.9 TU, respectively (note nearly identical values with depth), provide a baseline for modern tritium input values. The uniformity of tritium values in piezometer nest C corroborates horizontal flow of recently recharged groundwater (see earlier discussion). However, without further dating using SF_6 or $^3H/^3He$, the exact age of groundwater cannot be known.

Only groundwater from piezometers A60 and B64 showed pre-bomb tritium values of less than 0.8 TU. Groundwater samples from A35 and E105 are likely a mixture of pre-bomb and recent recharge. Groundwater in piezometer A60 may reflect travel along a flow path originating from the north, either directly from the uplands or via outwash of the Skunk bedrock valley. Groundwater from B138 in limestone is within the analytical precision limit of a pre-bomb signature, so it is likely pre-bomb as well. Groundwater in the Mississippian limestone from the St. Louis Formation to the Maynes Creek (Gilmore City) Formation also shows a pre-bomb signature in central Iowa (Simpkins et al., 2002). Further discussion of the tritium analysis and possible recharge areas is presented in the groundwater model section.

Groundwater Geochemistry and Water Quality

Redox Conditions

Groundwater at depth is under reducing conditions, as evidenced by lack of measurable dissolved O_2, lack of NO_3-N, high dissolved Fe concentrations, the presence of NH_4, and presence of H_2S and CH_4 (Tables 6 to 9). The presence of CH_4 in the groundwater indicates that the electron acceptors O_2, NO_3, Mn, Fe, and SO_4 have been depleted or nearly depleted and that methanogenesis is occurring, allowing for the reduction of CO_2 to CH_4 (Drever, 1997). Concentrations of CH_4 varied considerably between sampling locations (Table 6). However, in general, CH_4 concentrations are lowest in the shallow piezometers and higher at depth. This correlates well with the N_2O data (Table 6) that suggests denitrification is occurring in shallow groundwater and may be the primary reaction at shallow depths. A H_2S odor is noticeable while sampling the deeper piezometers, indicating that some SO_4 is also being reduced. Presence of NH_4 in this geochemical environment generally reflects organic matter decaying into amine compounds (Simpkins and Parkin, 1993).

Concentrations of CH_4 for the groundwater near Ada Hayden Lake (Table 6) are much less than those found by Simpkins and Parkin (1993) and Parkin and Simpkins (1995) in till and loess south and west of Ames, Iowa. They found CH_4 concentrations of 2688 µmol/L in late Wisconsinan loess and hypothesized that methanogens utilized organic carbon in the till and loess to reduce CO_2 to CH_4. The maximum CH_4 concentration measured during this study was 195.7 µmol/L in outwash at piezometer B64 (Table 6). The lower CH_4 concentrations found in groundwater from the outwash around Ada Hayden Lake are interpreted to result from lower organic carbon content compared to the Wisconsinan till and loess. The turbulent depositional environment of the outwash is not conducive to deposition or preservation of organic carbon. Also, the groundwater residence time in the outwash is much less than in till, resulting in less time for methanogenesis to occur. This explanation is corroborated by the results of the tritium analysis presented in the previous section. The highest concentration of CH_4 was sampled from groundwater (B64) that is pre-bomb in age.

In general, groundwater from piezometers screened in the outwash units was found to have high dissolved Fe concentrations (mean Fe concentration = 4.54 ppm). Groundwater from piezometers screened in bedrock was also high in Fe concentration (mean Fe concentration 2.94 ppm). High Fe concentrations are consistent with what is found throughout the Ames aquifer, where Fe is a concern for maintaining well screen efficiency for municipal supply wells (Simpkins and Christianson, 2007).

Nitrate

During the sampling period, NO_3-N was consistently detected from only the shallow piezometers at nests A and C (A15, C15, C35)(Table 7). For all deeper piezometers, NO_3-N was not detected, presumably because it had been reduced to N_2O. A slight decrease in NO_3-N values was observed during the sampling period, with the trend being most prevalent in A15 and C35 (Figure 21). The cause of the NO_3-N decline is unknown, but after one year of sampling it does not appear to be a seasonal trend. One possible explanation for the decrease in NO_3-N is that the groundwater was oxidized during piezometer installation allowing NH_3-N (NH_4) in groundwater to convert initially to NO_3-N. Groundwater may have returned to more reducing conditions during the study period. However, this hypothesis is not corroborated by dissolved O_2 measurements. More long-term monitoring is necessary to help establish the reasons for the trend and its implications for the future. High concentrations of NO_3-N were also found in groundwater from shallow piezometers at nests G, H, and J (G16, H10, J8.5)(Table 7). These piezometers were only sampled twice during the study period and it is unknown if the concentration of NO_3-N at those locations has changed significantly

Samples from the piezometers that consistently had the highest concentrations of NO_3-N (A15, C15, C35) also had higher concentrations of N_2O (Table 6), suggesting that denitrification is occurring in the vicinity of the piezometer. The production of N_2O occurs as an intermediate step in denitrification.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Steps in the denitrification process (Knowles, 1982)

$$2NO_3^- + 4H+ + 4e^- = 2H_2O$$

Denitrification expressed as a redox reaction (Drever, 1997)

The denitrification may be occurring in the presence of O_2. This is not a problem geochemically, because denitrification can occur in microsites in the presence of O_2 (Parkin, 1987). The presence of N_2O and NO_3-N together may indicate that there is a steady flux of NO_3-N into the system and that microbes are taking advantage of it by denitrifying the nitrate occurring at shallow depths.

Chloride

Chloride is often used with nitrate to trace contamination from agricultural sources and to provide evidence on denitrification (Altman and Parizek, 1995). Concentrations of Cl range from 1.8 to 56.1 mg/L. In general, shallow groundwater shows higher concentrations than older and deeper groundwater, particularly at nests A and B (Table 9). Groundwater samples at piezometer B13 shows the influence of Cl on the wetland recharge area and the movement of water at depth. Groundwater at nest C shows elevated Cl concentrations, which could indicate road deicer contamination of groundwater from the residential area southwest of the lake. Samples from nests D and E reflect the Cl concentration of lake water.

Phosphorus

Phosphorus concentrations in the groundwater were found to be very high and are of great concern for maintaining water quality in the lake. Mean total-P concentrations for individual piezometers ranged from 5.9 µg/L to 365.8 µg/L (Table 7). A significant portion of the total-P is soluble reactive phosphorus (SRP) with mean values ranging from 1.5 µg/L to 429.1 µg/L (Table 7). An average of 66 percent of the total-P was SRP, with percentages ranging from 8 to 132 percent. Percentages greater than 100 percent are due to analytical error and can be assumed to be 100 percent. SRP is thought to be the more mobile P form in groundwater and the most accessible form of P to aquatic organisms, although other forms of P can also be used by aquatic organisms (Simpkins et al., 2001).

Phosphorus concentrations were generally larger with depth although concentrations in the bedrock were slightly lower than found in the outwash. As has been observed elsewhere, P concentrations in the groundwater tend to increase as the groundwater becomes more reducing (MPCA, 1998; Carter et al., 2005). This also correlates with phosphorus levels increasing as the iron level also increases, as has also been observed in the groundwater system at Clear Lake (Simpkins et al., 2001). This relationship has been attributed to the reductive dissociation of Fe-P minerals or the dissociation of Fe-hydroxides and the subsequent release of adsorbed phosphorus (Shenker, 2005), although there is no evidence for this mechanism occurring in late Wisconsinan materials in Iowa (Carter et al., 2005).

Saturation Indices

Groundwater at all the sites was found to be saturated with respect to carbonates (calcite and dolomite; Table 10). This is expected considering the large amount of carbonate present in the outwash and that Mississippian carbonate comprises most of the bedrock in the area. Where the groundwater has been shown to contain some dissolved oxygen (A15, A35, C15) the groundwater is highly undersaturated with respect to Fe-bearing minerals (siderite and iron sulfides). Groundwater that is under reducing conditions was found to be saturated, or nearly saturated, with respect to iron bearing minerals because of the high dissolved Fe concentrations.

Groundwater under reducing conditions, particularly those from the outwash units, was found to be saturated or nearly saturated to P-containing minerals, in particular, hydroxyapatite, $Ca_5(PO_4)_3(OH)$. Phosphorus will sorb to Fe minerals, or precipitate as

Ca-P minerals (hydroxyapatite), under oxic (non-reducing) conditions. Because the groundwater at Ada Hayden Lake is reducing, the P in the groundwater will not sorb to Fe minerals or precipitate out of solution (groundwater is saturated with respect to those minerals) and much of it may be transported advectively to the lake.

Steady-State Groundwater Flow Model

Model Construction

A 3-D, finite-difference, groundwater flow model, MODFLOW-2000, (Harbaugh et al., 2000) was used to simulate groundwater-lake interaction for Ada Hayden Lake. Stratigraphic information from boreholes and driller's logs (n = 74) was entered into GMS 6.0 – Groundwater Modeling System (Environmental Modeling Systems, Inc. Provo, UT). The GMS software is designed to help build a 3-D solids model of the stratigraphy prior to discretizing the model (Figure 22). The building of the stratigraphic model allows the user to pick stratigraphic boundaries and view the geology during the process, so it is not a totally automated process. The discretized model as built in GMS was then imported into the GUI Groundwater Vistas (GV) version 5.0 (Environmental Simulations, Inc., Reinhold, PA) to refine the grid, define boundary conditions, and calibrate the model. Although GMS could be used entirely for the modeling exercise, GV proved to be more stable and allowed for more user control of model parameters, solvers, and automated parameter estimation. GMS, by comparison, is a "black box."

The block-centered grid consisted of 130,618 active cells in 101 rows, 93 columns, and 15 layers. The active model domain covered an area of approximately 2,720 ha

(6,720 acres)(Figure 23 and Figure 24). The maximum cell size for the model grid was 102 m (335 ft) by 119 m (392 ft) with much smaller cells near the lake. The maximum relative change in adjacent cells was set at 1.5:1. The PCG2 solver was used with a convergence criteria set at 1 x 10^{-4} ft. Early in the modeling exercise the SOR solver was used as it seemed to be more stable; however, it often produced errors in the lake water balance.

Five hydrostratigraphic units (based on K) were identified: modern alluvium, upper confining unit (Wisconsinan and Pre-Illinoian till), outwash (Wisconsinan and Pre-Illinoian), lower confining unit (till and loess), and limestone bedrock (Figure 25 to Figure 27). The Block-Centered Flow Package (BCF6; Harbaugh et al., 2000) was used with variable layer elevations assigned on a cell by cell basis to better represent the stratigraphy.

Most of the boundaries specified in the model domain (Figure 23) were extracted from a regional 2-D analytic element model (Simpkins and Christianson, 2007). Location of no-flow boundaries on the north, west, and southern portions were based on groundwater divides and flow lines from that model. The South Skunk River comprises a head-dependent boundary along the eastern edge of the model domain (Figure 23 and Figure 24) and was simulated in Layer 1 using the RIV Package (Harbaugh et al., 2000). River stage for all cells was estimated using the mean stream stage for 2006 from USGS gauging station 05470000 (South Skunk River near Ames, Iowa) and an estimated stream gradient of 0.00087 (USGS, 2007). The stream gradient was estimated based on a USGS 1:24,000 topographic map (Ames East; USGS, 1975). Tributary streams entering the lake were simulated using the Stream Flow Routing Package (SFR1; Prudic et al., 2004).

Use of the SFR1 package was necessary due to implementation of the LAK3 Package, which requires the use SFR1 for the surface water component of the lake water budget and calculation of lake stage.

Recharge (R) was defined for two zones – an alluvial lowland area and a till upland area. An initial recharge value of 6 in/yr was used for the uplands and 6.5 in/yr for the lowlands. Alluvial deposits were given a higher recharge value due to their higher K and ability to transmit water into the subsurface more quickly. The upland areas, consisting almost entirely of till deposits, were given a lower recharge value because more precipitation runs off there in comparison to the alluvial surface.

Ada Hayden Lake and the northern wetland complex were simulated using the LAK3 Package (Merritt and Konikow, 2000). Precipitation data were obtained from the National Weather Service station (Ames-8-WSW) located about 12.8 km (8.0 mi) southwest of Ada Hayden Lake; the value for 2006 of 94.0 cm (37.00 in), which is 10.3 cm (4.06 in) above the 1951 to 2006 mean of 83.7 cm (32.94 in) was used. Evaporation from the lake surface was set at an annual free water-surface value of 99.1 cm/yr (39.0 in/year)(Farnsworth et al., 1982), which is more than the 91.44 cm/yr (36 in/yr) used in the analytic element model (Simpkins and Christianson, 2007).

Stream outflow from the lake was simulated in the model by allowing the SFR1 Package to reference a rating curve table of stream depth to flow. Discharge at the spillway on the southeast side near piezometer nest D (Figure 10) was measured at various lake stages during the spring and summer of 2007. Measured values were fit to a rating curve (Figure 28) and entered into the flow table in the model. This feature allows the correlation of discharge at the outlet to actual lake stage; discharge is zero when the lake stage drops below the level of the spillway at the outlet structure.

Calibration targets included mean hydraulic heads from all 23 piezometers installed as part of this project; one-time water level measurements from 10 private wells listed in the GEOSAM database (IGS, 2007); water levels from four geotechnical borings (Allender Butzke Engineers Inc., 1999); and mean lake stage (Figure 29). Private wells and geotechnical borings, although of limited accuracy, provide historical data for the northern part of the model domain where data are lacking. Experience with the siting of swine lagoons in Iowa suggests that geotechnical borings in till routinely underestimate hydraulic heads due to the inability of investigators to wait for static equilibrium to occur (Simpkins et al., 2002). No flux targets were used in the model. Automated parameter estimation often works best, and has less uncertainty, when multiple types of calibration targets (e.g., head and baseflow targets) can be used (Hill, 1998; Hunt et al., 2006). Baseflow to the South Skunk River was not used as a calibration target because only a small portion of the river is represented in the model.

Initial Model Results

Initial parameter values were based on previous investigations of the Ames aquifer and values from other studies done in Iowa (Table 11). Values of K used in the initial model were higher than observed in the slug tests from this study. As discussed earlier, K values obtained from slug tests often underestimate K at larger scales. The geometric mean K of outwash around Ada Hayden Lake from slug tests was 2×10^{-4} m/s (56.7 ft/d). Sendlein and Dougal (1968) determined a K value of 9.4×10^{-4} to 2.6×10^{-3} m/s (268 to

732 ft/d) for the outwash within the Skunk bedrock valley north of Ada Hayden Lake. A initial value of 152.4 m/d (500 ft/d) was used for the outwash – within the range determined by Sendlein and Dougal (1968). The calibration of the initial model had a mean absolute difference (MAD) of 2.14 m (7.02 ft).

The automated parameter estimation program PEST (Watermark Computing, 2005) was used to improve model calibration and better estimate the model parameters. PEST uses an inverse estimation method (Marquardt-Levenberg algorithm) to minimize the difference between simulated results and observed target values (the residual, or objective function) by adjusting specified parameters. PEST allows the user to assign a weight to targets (observed values) based on the confidence in the measurement. Head data collected as part of this project were given a weight of 10. The accuracy of these data are very good because absolute elevations were obtained for all piezometers. Boring data obtained from Allender Butzke Engineers Inc. (1999) for the till were given a weight of 5. One-time water level targets from the private wells were given a weight of one. Absolute elevations and locations of these targets are not well known and could be in error as much as a quarter section horizontally and 4.5 m (15 ft) vertically. Water levels measured during well installation may not represent an equilibrium hydraulic head value.

The PEST analysis proved somewhat useful but it did not improve the calibration significantly from the initial calibration, nor was it able to provide narrow confidence bands for parameter values. This failure most likely resulted from a lack of reliable head targets in the uplands and lack of flux measurements. PEST was also affected by the instability associated with dry cells. The water table may reside within the bedrock in the northeast part of the model near the South Skunk River where the bedrock is near the surface (or crops out). This caused convergence problems, because cells in this area oscillated between wet and dry and caused the model to become unstable. As suggested by Harbaugh et al. (2000), the resaturation parameters and the number of inner iterations used by the solver were adjusted to try overcome the stability issues. However, this proved to offer little improvement. Sensitivity analysis showed that the most sensitive parameters were recharge in the uplands, vertical K of the till, and horizontal K of the outwash, alluvium, and bedrock (Figure 30). Recharge and the vertical K of the till were significantly more sensitive than the other parameters.

Results from steady-state simulations are consistent with previous conclusions (e.g. water-table mapping and stable isotopes) indicating that groundwater is flowing into Ada Hayden Lake from the north, west, and southwest and leaving the lake on the eastern side flowing towards the South Skunk River. Ada Hayden Lake is a classic flow-through lake (Figure 31 and Figure 32).

The final calibrated model indicated reasonable agreement with observed data (Figure 33). The mean error was 0.48 m (1.58 ft) and the MAD was 1.66 m (5.43 ft). The largest residuals were in the upland areas for one-time water level targets from private wells. At Ada Hayden Lake where water levels in piezometers from this study show the highest level of accuracy, the modeled heads fit much closer to observed heads (Figure 33). The mass balance error for the model was -0.008 % (Figure 34).

Parameter values used in the final calibrated model (Table 11) are consistent with those used in the regional analytic element model for the Ames region (Simpkins and Christianson, 2007) and other studies done in the area. In that model, a K value of 56 m/d (184 ft/d) for the alluvium around the lake was necessary to simulate the lake stage.

This value is at least one order of magnitude less than estimated for the Ames aquifer in the Downtown and Southeast well fields. In the present study, K values of 54 m/d (177 ft/d) for outwash and 5.2 m/d (17 ft/d) for the recent alluvium were necessary for calibration. Simpkins and Christianson (2007) used a recharge value of 6.4 in/yr to calibrate their analytic element model – about 19 percent of the 1951 to 2006 mean precipitation. For the present study a recharge value of 7.3 in/yr on the uplands and 7.8 in/yr on the lowlands was necessary for model calibration – about 19 percent of the 2006 precipitation. Values of K for upland till were 8.5 x 10^{-3} m/d (2.8 x 10^{-2} ft/d), which is representative of unweathered late Wisconsinan and Pre-Illinoian till in the region (Simpkins and Parkin, 1993; Simpkins, 2006). For limestone, the model value of K = 6.2 m/d (20.4 ft/d) is similar to values determined by Ryan (1993) from slug tests in the St. Louis Formation near Story City. Values of K for the lower till/loess unit in the model (7 x 10^{-10} m/d; 2.0 x 10^{-4} ft/d) are at the lower limit of K values found for these units in central Iowa (Simpkins and Parkin, 1993; Seo, 1996).

Total groundwater flow into the South Skunk River from the west within the model domain was calculated to be 11,865 m^3/d (419,022 ft^3/d). This value may be questionable because the South Skunk River is a boundary condition that is not explicitly modeled. Underflow and head distribution on the eastern side of the river were not accounted for in the model. Hence, the baseflow contributions from upstream, and from the east side of the river can not be simulated in the model.

The lake water balance demonstrates that Ada Hayden Lake is a groundwater-dominated, flow-through lake, and that stream inflow comprises only a minor percentage of water to the lake (Table 12). Calculations showed a 0.06 percent water balance error and were based on simulation of stage to an absolute lake elevation of 273.41 m (897.0 ft), which is slightly less than the mean stage of the observed 273.53 m (897.4 ft)(Table 12). Groundwater discharge to the lake is 7,800 m^3/d (275,470 ft^3/d) and approximately 85 percent of water entering the lake (Table 12). Streamflow at the outlet is the largest output from the lake (159,370 ft^3/d). The dominance of groundwater input is consistent with observations made both during this study and by Downing (2006), who observed that the tributaries entering the lake show streamflow only during storm events or in the early spring due to snowmelt. The northern tributary often shows more sustained baseflow; however, as discussed earlier, that streamflow is sequestered in the large wetland and evaporates or recharges the groundwater system directly rather than flowing directly to the lake. The model shows that all three tributaries convert from gaining to losing streams when they enter the alluvium adjacent to the lake, thus recharging groundwater that flows to the lake. The three tributaries combined contribute less than one percent of the total water entering the lake (Table 12) – results consistent with the analytic element model (Simpkins and Christianson, 2007). Although the water balance shows water outputs as divided between surface water outflow, groundwater outflow, and evaporation (Table 12), the relative proportion of groundwater and surface water outflow is partially dependent on the lake stage; i.e., when the lake stage drops below the outlet, water leaves the lake as evaporation and groundwater.

Distribution of Groundwater Discharge to the Lake

Similar to many previous studies of groundwater-lake interaction, most groundwater discharge to Ada Hayden Lake occurs near the shore (Figure 35). Groundwater discharge to the lake from the surrounding aquifer as calculated by the LAK3 package was quantified along two west-east transects – one in the north basin (model row 84) and one in the south basin (model row 97). The transect locations were chosen to try and minimize the effects of groundwater flow from multiple directions (previous studies used 2-D cross sectional models).

Results show that most groundwater discharge occurs near the lake shore along the two transects. Small peaks occur in groundwater discharge to the lake (Figure 35). The cause of these peaks is uncertain; however, it may be related to the model cell configuration. Where a lake cell is isolated in a different layer and not surrounded by other lake cells, it receives discharge for multiple sides of the cell. For example, along the transect in the north lake basin in model layer 4 (Figure 36), some cells are able to receive discharge from the north. At this point along the transect the calculated groundwater discharge increases. In any case, groundwater discharge to the lake decreases further from the lake shore in more or less a logarithmic fashion.

Particle Tracking

Particle tracking was implemented using the USGS program MODPATH (Pollock, 1994) to examine potential sources of contaminants and the size of the ground-watershed for the lake. Particle tracking simulates the flow of infinitely small particles within a groundwater model. The particle within the model is transported by advection using model calculated hydraulic gradient and K, with user specified porosity values – transport by dispersion is not simulated. Particles were tracked backwards to their point of origin from all model cells at the edge of the lake in layers where the lake is intersected (i.e., Layers 1 to 5; Figure 37). Particles were also tracked backwards for 55 years ("pre-bomb") from nested piezometers installed for this study (Figure 38). Porosity values were estimated to be 0.25 for the outwash and alluvium (Schwartz and Zhang, 2003), 0.01 for the till (Helmke, 2003) and 0.05 for limestone bedrock (Schwartz and Zhang, 2003).

Results from the particle tracking for groundwater entering the lake traced back to the point of origin show the approximate extent of the ground-watershed for Ada Hayden Lake (Figure 37). Much of the ground-watershed lies to the north and west of the lake, with most of this land being agricultural. Part of the residential area to the southwest of the lake is also within the ground-watershed. The model indicates that groundwater does not flow along a flow path all the way from Peterson Pits to Ada Hayden Lake via the Skunk bedrock valley. A groundwater divide exists along the Skunk bedrock valley as suggested earlier by Sendlein and Dougal (1968).

Particle tracking from the location of piezometer screens shows that groundwater from the deeper piezometers may originate from a much further source than groundwater that flows into the lake (Figure 38). The flow paths for piezometers B138 and E105 (Figure 38) extend beyond any of the flow paths that end at the lake (Figure 37). In contrast, groundwater recharging in the uplands flows along a nearly vertical flow path until it reaches either bedrock or outwash and then flows along a more horizontal flow path to the lake.

It is difficult to match the particle tracking analysis to the tritium data. Piezometers A60 and B64 and possibly B138 had a tritium signatures indicating groundwater older than about 55 years (Table 5). Results from the particle tracking show that groundwater from B64, which showed a pre-bomb tritium signature, entered the flow system 18 years prior to reaching the piezometer. The particle track for B138 shows that groundwater entered the system 49 years prior to reaching the piezometer. This fits reasonably well with tritium data for piezometer B138. The particle track for E105 shows a flow path under the lake, entering the flow system more than 55 years ago. Bethke and Johnson (2002a,b) note that groundwater age dates may deviate from groundwater models that assume simple piston (plug) flow, which assumes only advection. A more accurate conceptualization would need to account for diffusion, dispersion, and cross-formational flow in addition to advection. Groundwater is also a mixture of waters from different sources. This mixture may be even more complex near a regional discharge source such as the South Skunk River. The tritium values for E105 may represent such a mixing effect. Also, variations in the porosity values used during the particle tracking have an effect on the calculated residence time. Estimates of the porosity were used in this study and actual values may be different.

Phosphorus Budget

Model simulations confirm that groundwater is a major contributor of P to the lake. Based on the modeled groundwater discharge to the lake and measured SRP concentrations, groundwater delivers between 2.8 and 830 kg of P per year to the lake. This wide range represents the 10^{th} percentile (0 μg/L; the MDL of 1 μg/L was used for analysis) and the 90^{th} percentile (292 μg/L) for measured SRP concentrations of groundwater entering the lake over the study period. About 259 kg/yr of P is transported to the lake via groundwater assuming an arithmetic mean SRP concentration of 91 μg/L.

The northern tributary may be a greater contributor of P to the lake. Curve number modeling estimates that the northern tributary contributes between 460 kg/yr (no loss of P in the wetlands) and 231 kg/yr (50% loss of P in the wetlands) to the lake; but, these may be overestimates. Even during high flow (e.g., spring of 2007) almost no water from the northern tributary flows directly into the lake. In the spring of 2007, water flowed into the lake from the northern tributary only when the wetland became too full and water spilled over the walking path on its way to the lake. Hence, there may be very little P entering the lake from the northern tributary and groundwater may be the largest contributor. Using the arithmetic mean SRP concentration for groundwater entering the lake, and assuming a 50 percent loss of P in the wetlands, the total P load to the lake is 617 kg/yr. Groundwater thus contributes 42 percent of the total P load, comparable to estimates from other studies done on Midwestern lakes (Brock et al., 1982; Brown, 1986; Shaw et al., 1990). The tributaries combined account for 54 percent of the P load, with the northern tributary contributing 38 percent and the southern and central tributaries each contributing 8 percent. Precipitation and dryfall account for 4 percent of the P load.

Concentrations of P for the mixed lake were estimated using the Canfield-Bachmann (1981) model. An annual flushing rate of 0.69 yr^{-1} was estimated for Ada Hayden Lake using calculated inflow of 3,359,133 m^3/yr from all sources (groundwater, precipitation, stream flow). Using the calculated P load to the lake, the concentration of P in the lake was estimated to be between 59.7 and 165.9 μg/L (no loss of P in the wetlands) and 41.1 to 154.6 μg/L (50% loss of P in the wetlands). The range of values reflects the 10^{th} and 90^{th} percentiles of SRP concentrations. The arithmetic mean SRP concentration yields estimates of 104 μg/L and 80 μg/L for no loss in the wetlands and a 50 percent P loss in the wetlands, respectively. These values are slightly greater than predicted by BRAA (2000) and Antosch (1982) and lie at the upper end of values measured by Downing et al. (2006)(Table 13). In the latter case, the large differences could reflect greater P sequestration in the lake sediments than calculated with the standard P sedimentation coefficient in the Canfield-Bachmann model. Downing et al. (2006) reports a mean total P concentration for the upper 5 meters to be 20 and 24 μg/L for the north and south lakes respectively. However, at depth, total P concentrations greater than 100 μg/L are common, especially in the summer. The anoxic environment present in the deeper parts of the lake (Downing et al., 2006), which may be due to the inflow of low redox groundwater, may control the release and sequestration of P in the lake (Miao et al., 2006).

It is interesting to note that estimates of mixed lake P concentration by BRAA (2000) are only slightly less than estimated in this study even though BRAA (2000) neglected the groundwater component. Groundwater is not only a major contributor of P, but is also the largest contributor of water to the lake. Thus, including the groundwater component in the lake model increases not only the P load but also total amount of water entering the lake, in effect increasing the flushing rate. According to the Canfield and Bachmann (1981; see equation on page 35 of the present study), the P concentration in the lake is inversely proportional to the lake flushing rate. In short, for a given areal P load (L), increasing the flushing rate will effectively decrease the P concentration in the lake. This explains why the estimates of P concentrations in the lake are similar among the different methods, despite their inclusion or exclusion of the groundwater component (Table 13).

Transient Groundwater Flow Model

Ada Hayden Lake as an Emergency Water Supply

A transient simulation was used to predict the effects of pumping from the lake as part of an emergency water supply – a condition similar to that which occurred in the 1976-77 drought. A steady state simulation was conducted under drought conditions in order to obtain initial conditions for the transient simulation. All parameters from the initial steady state model remained the same except recharge. Recharge was reduced by 66 percent (2.45 in/yr for the uplands and 2.61 in/yr for the lowlands) to simulate drought-like conditions. Results from the steady-state drought simulation (no pumping from the lake) predicted a lake stage of 272.96 m (895.53 ft), or a decline of about 0.52 m (1.7 ft) from normal lake stage.

For the transient pumping simulation, a single stress period of 365 days with a one day time step interval was used to simulate pumping directly from the lake at a rate of 6 x 10^6 gal/d (the average pumping rate from the summer of 1977 recorded in city records). The LAK3 Package is able to easily handle pumping from the lake by simply specifying a lake withdrawal term in the MODFLOW input files. The specific yield for the various units was estimated at: 0.04 for till, 0.14 for limestone, and 0.22 for both alluvium and outwash (Seo, 1996; Schwartz and Zhang, 2003).

Model simulations show that lake stage decreases with time under pumping conditions (Figure 39). After one week of pumping, the predicted lake stage of 272.74 m (894.73 ft) indicated a decline of 0.69 m (2.27 ft) from normal lake stage. After one month (30 days) of pumping the predicted decline in the lake was slightly greater at 1.36 m (4.45 ft). These simulated declines in the lake level are less than those observed when the lake was pumped during the 1977 drought. One explanation for this discrepancy is that three separate lake basins existed during summer of 1977 (Figure 11) and water was pumped from the south basin where the drop in stage was observed. Presently, the north and south basins are connected and treated as one basin in the model; hence, pumping will have less of an effect on lake stage because there is a larger reservoir of water.

Longer term, continuous pumping causes much greater declines in lake levels. The predicted lake stage under pumping conditions after 365 days is 268.19 m (879.89 ft) – a decline of 5.2 m (17.11 ft) from normal lake stage (Figure 40). The hydraulic gradient on the eastern side of the lake is reversed and groundwater flows into the lake from the river. The lake converts from a flow-through lake to a discharge lake and, because the stage is below spillway elevation, the only outflow from the lake is through pumping or evaporation.

A problem with the simulation of pumping is that the cone of depression extends to the edge of the model domain and may induce a boundary effect on the solution. After 38 days of pumping the natural gradient is reversed and groundwater flows from the river to the lake. At this time the river acts as a source of water to the model. In a real pumping scenario, this may not occur. Presumably, the cone of depression should extend beyond the South Skunk River to the east, effectively disconnecting the river from the aquifer. Hence, a larger model with a boundary condition farther away from the lake will be needed to fully test the effects of long-term pumping on lake stage and flow in the South Skunk River.

Proposed Ada Hayden Park Well Field

The calibrated model was used to predict the effects of placing a municipal well at Ada Hayden Park. For this simulation, a well was placed just west of the north lake basin within the coarse gravel outwash (row 85, column 55, layers 3 to 5). For this simulation, the northern wetland was removed from the model to increase model stability. The static water level prior to pumping was 274.44 m (900.38 ft) and the pumping rate was 1000 gpm. The cone of depression as a result of pumping extends to the western side of the lake. After 17 days of pumping the cone of depression is great enough to reverse the natural hydraulic gradient, allowing the lake to become a source of water for the well. After one year of pumping, a cone of depression lowers the water level in the well to 270.69 m (888.1 ft)(drawdown of 3.75 m; 12.28 ft)(Figure 41) – comparable to the 888 ft observed by Simpkins and Christianson (2007) using a steady-state, 2-D, analytic element model. The calculated lake stage after one year of pumping is 273.31 m (896.7 ft) which equates to a decline of about 0.09 m (0.3 ft) from normal, non-pumping, condition. This is less than the lake stage decline of 0.67 m (2.2 ft) predicted by Simpkins and Christianson (2007) who also used a lower initial lake stage of 896.3 ft and pumped from a larger screened interval that included the sandier alluvium. Presumably, if the northern wetland were allowed to fill with water in the area of the well it would also act as a major source of water for the well. The effect that induced recharge from the wetland would have on water quality from the well is unknown, but it is presumed that the water quality would be worse (i.e., higher concentrations of P and fecal coliform) than if the wetland was not a source of water for the well. In any case, pumping a new well in the large wetland area in the northwest part of the park at rate of 1000 gpm may not affect the lake level greatly. It does, however, induce flow from the lake, which could invoke the “groundwater under the influence of surface water” rule and require additional water quality testing.

SUMMARY AND CONCLUSIONS

Hydraulic head data, stable isotopes, and a 3-D finite-difference groundwater flow model demonstrate that Ada Hayden Lake is a flow-through lake, with groundwater entering from the north, west, and southwest while leaving on the east and southeast sides of the lake where it then flows down-gradient in the Ames aquifer. Surface water constitutes very little total water input to the lake – groundwater accounts for nearly 85 percent of the water under steady-state conditions. Surface water in tributaries to the lake enters the lake mostly during storm events. Surface water in the largest of the three tributaries, the northern tributary, is retained in the wetlands, eventually evaporating or recharging the shallow aquifer. The signature of the enriched wetland water recharging the aquifer can be seen in the stable isotopes from the shallow wells between the wetland and the lake.

Groundwater immediately adjacent to the lake contains high concentrations of P; thus, groundwater flow is a major source of P to the lake. The lake is also a source of P to groundwater on the down-gradient side of the lake. The mean concentration of SRP from piezometers monitored during this study was 93.6 μg/L. The presence of P in high concentrations is consistent with reducing geochemical conditions and saturation with respect to P-bearing minerals – phosphorus can be easily transported to the lake and is not retained within the sediments. Only the northern tributary is potentially a greater source of P to the lake, assuming that it enters the lake directly and does not recharge the aquifer. Given the young age of most of the water (from ^{3}H data and the particle-tracking data) from the model, the source of P may be intensive row-crop and animal agriculture in the watershed. High values of P in groundwater are not uncommon in areas with intense agriculture (MPCA, 1998; Burkart et al. 2004).

It is also possible that the source the P is from initial cultivation of pre-settlement prairie soils. Cultivation of soil has shown to reduce the amount of organic matter within soil and P content of soil may decrease by as much as 29 percent (Tiessen et al., 1982). This P lost from the soil may then be transported with the groundwater. Tiessen et al. (1982) also note that the loss of P from soil does not decrease to a baseline value, but continues to decrease long after initial cultivation, presumably continuing to supply P to groundwater. Thus, soil cultivation is a potential source of P to groundwater at the lake. Unfortunately, the full mechanisms for release and transport of P in groundwater from soil cultivation are not well understood at present

Reducing the amount of P entering the system today and prevention of future P releases to groundwater are necessary to help maintain lake water quality in the future. The effectiveness of constructed wetlands in helping reduce P input to the lake from the tributary steams is not well known, nor is their interaction with groundwater at the park. Continuous monitoring of flow and nutrients in the tributary streams may be necessary to document their nutrient load to the lake and improve the nutrient budget calculations. More frequent (continuous) monitoring of flow and water quality in the constructed wetlands is also needed to document their effect, especially during storm events.

Controlling the P input to the lake from groundwater will require a different approach. The traditional approach would be to keep nutrients from initially entering the groundwater. Testing of soil P concentrations could be done in the surface- and ground-watersheds to assess whether additional P needs to be applied to maintain soil fertility.

Banning the use of P-containing fertilizers within the surface and ground-watersheds of the lake could also be enforced. Phosphorus bans have been effective and well received in Clear Lake, Iowa, as well as Minnesota, Wisconsin, and Maine. Such a measure may be even more important as more development occurs to the west and north of the lake where much of the watershed and ground-watershed reside. Remedial measures for P in the groundwater must be considered for the long term, because the residence time in the groundwater system is long in comparison to surface water.

The 3-D, finite difference, groundwater flow model predicts that Ada Hayden Lake can serve as an emergency water supply. Results of this study show that short term pumping of the lake should not result in significant lowering of the lake level. However, long-term pumping (greater than ~30 days) at rates similar to those in 1976-77 will produce significant declines in lake level and reverse the hydraulic gradient so that flow is induced from the South Skunk River. A larger scale groundwater model that extends beyond the South Skunk River is needed to fully test the effects of long term pumping on the lake levels.

Alternatively, a new well field could be established at Ada Hayden Park. Simulation of a single well, west of the northern lake basin, pumping at 1000 gpm showed that the well would induce flow from the west side of the lake and cause a decline of about 0.08 m (0.3 ft) in the lake level after one year. The potential regulatory issues of induced infiltration of surface water, along with trying to maintain water levels in the lake for emergency supply, make a new well field at Ada Hayden Park less desirable than other potential sites south of Ames.

Overall, it is important to recognize the hydraulic connection of Ada Hayden Lake with the Ames aquifer. Both the lake and the aquifer are very important to the City of Ames and both can be stressed greatly by drought and nutrient loading. Maintaining excellent water quality and water supply in the lake and the aquifer will require a community wide effort. The resource should never be taken for granted.

SUGGESTIONS FOR FUTURE WORK

Future investigations at the lake will be necessary to gain a better understanding of the hydrogeology and to protect water quality. The following areas are suggested for future work:

- Continued monitoring of the piezometers at the lake for water quality and hydraulic head in order to identify new water quality threats or trends;

- Create a larger scale groundwater flow model to simulate flow (and remove boundary effects) beyond the South Skunk River;

- Test soil P concentrations in the surface- and ground-watershed of the lake to assess whether additional P is needed to maintain soil fertility and to provide a basis for restricting P use;

- Monitor the lake stage and hydraulic heads in piezometers during lake pumpage. Analysis of these data would allow for more accurate storage terms and the possibility of calibrating a transient model to field data;

- Determine the age of groundwater with more precise methods such as sulfur hexafluoride (SF_6) and $^3H/^3He$ to help determine source areas and travel times of nutrients to the lake;

- Install piezometers in the uplands and in the Skunk bedrock valley north of the lake to better characterize the groundwater flow system, provide water quality data, and add calibration targets for future flow and contaminant transport modeling;

- Install continuously recording stream gages and water quality sampling equipment on the three tributaries to the lake to characterize the storm flow component and nutrient concentrations. This will improve the nutrient budget calculations and lead to better management of the lake resource.

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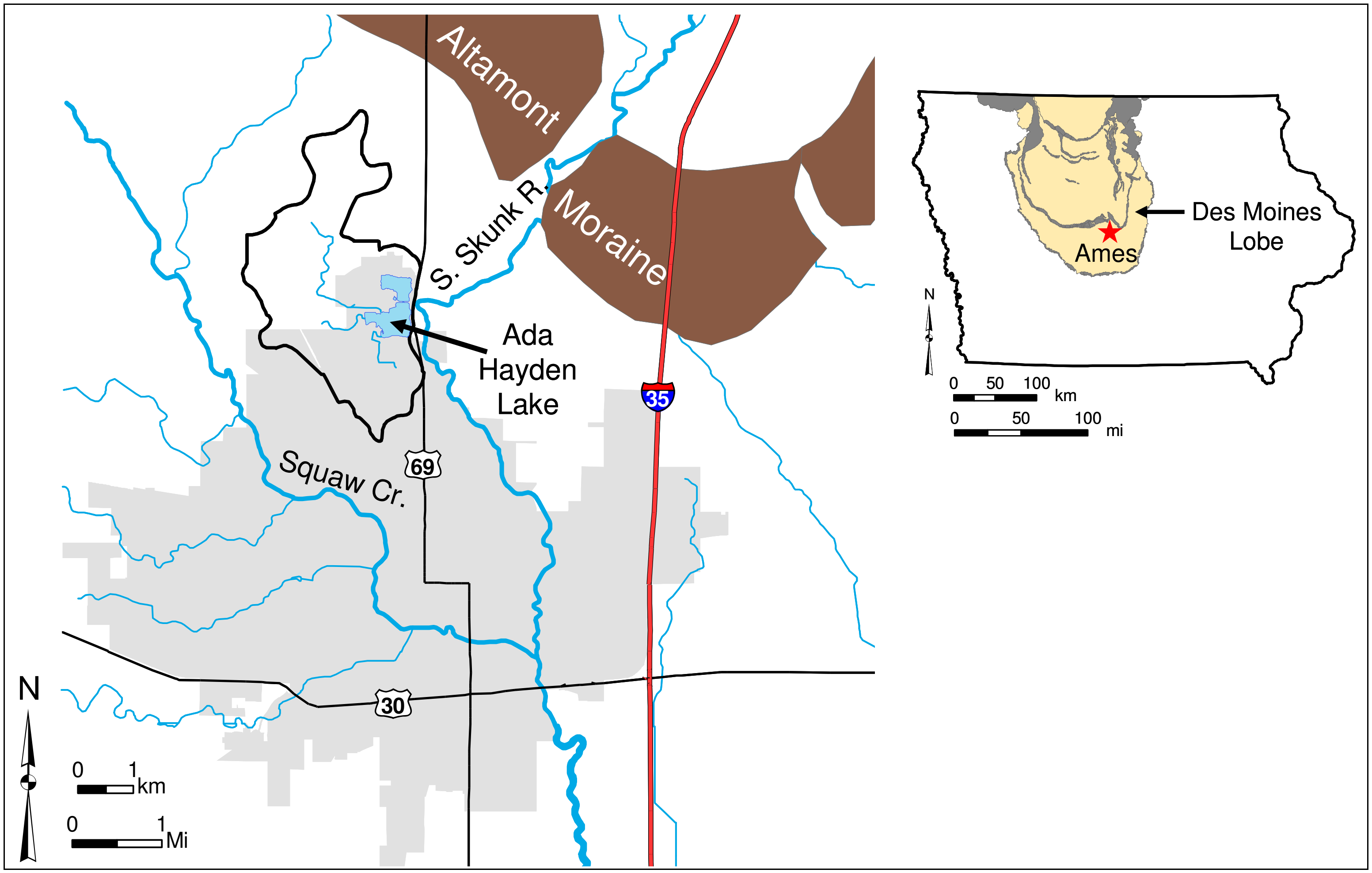


Figure 1. Location of study area within Iowa (inset). Gray area on larger map shows city limits of Ames, IA.

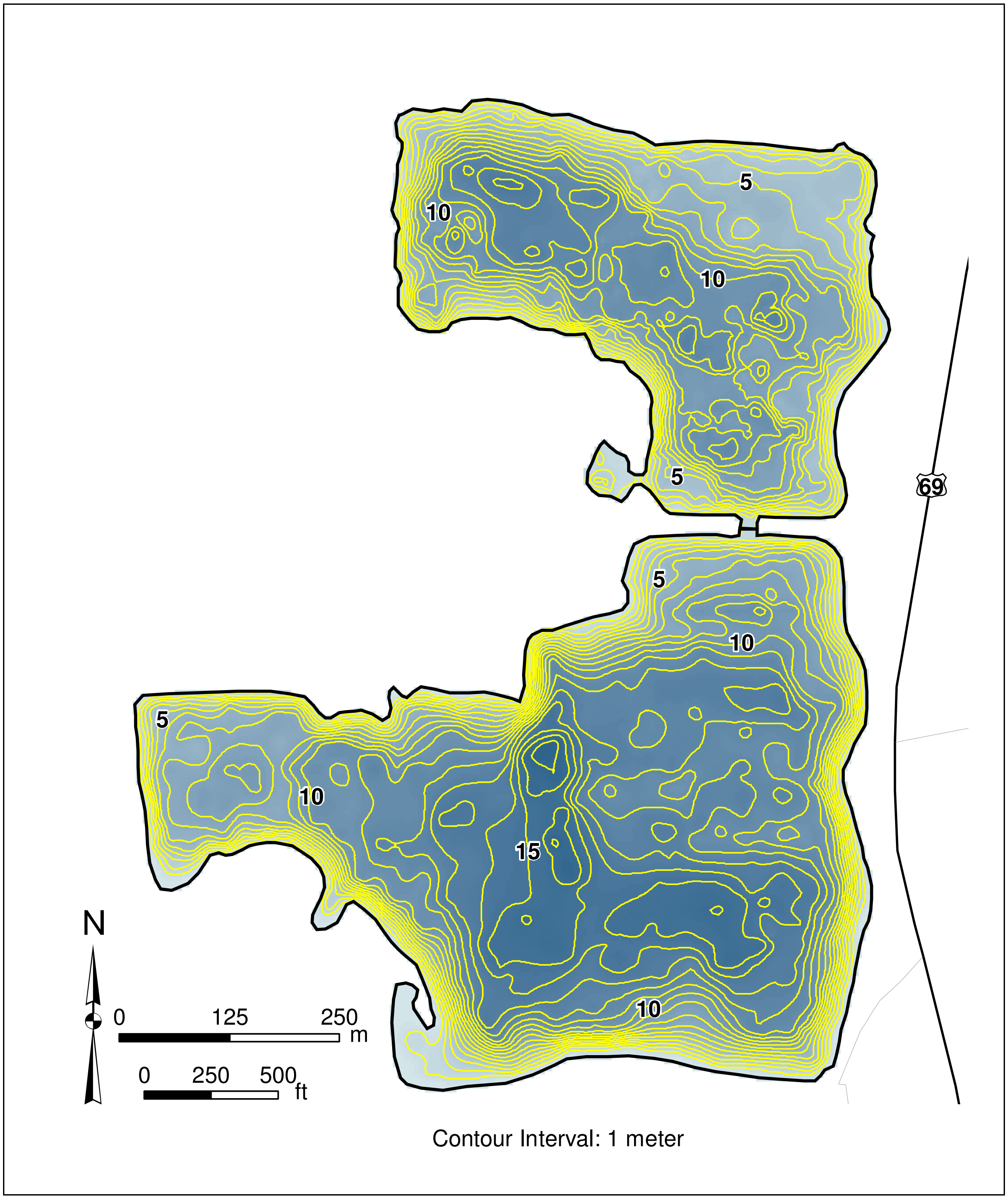


Figure 2. Bathymetry of Ada Hayden Lake. Note steep sides and a comparatively flat bottom due to its former use as a gravel pit. Dimensions given in text. Data provided by John Downing, Iowa State University (2007).

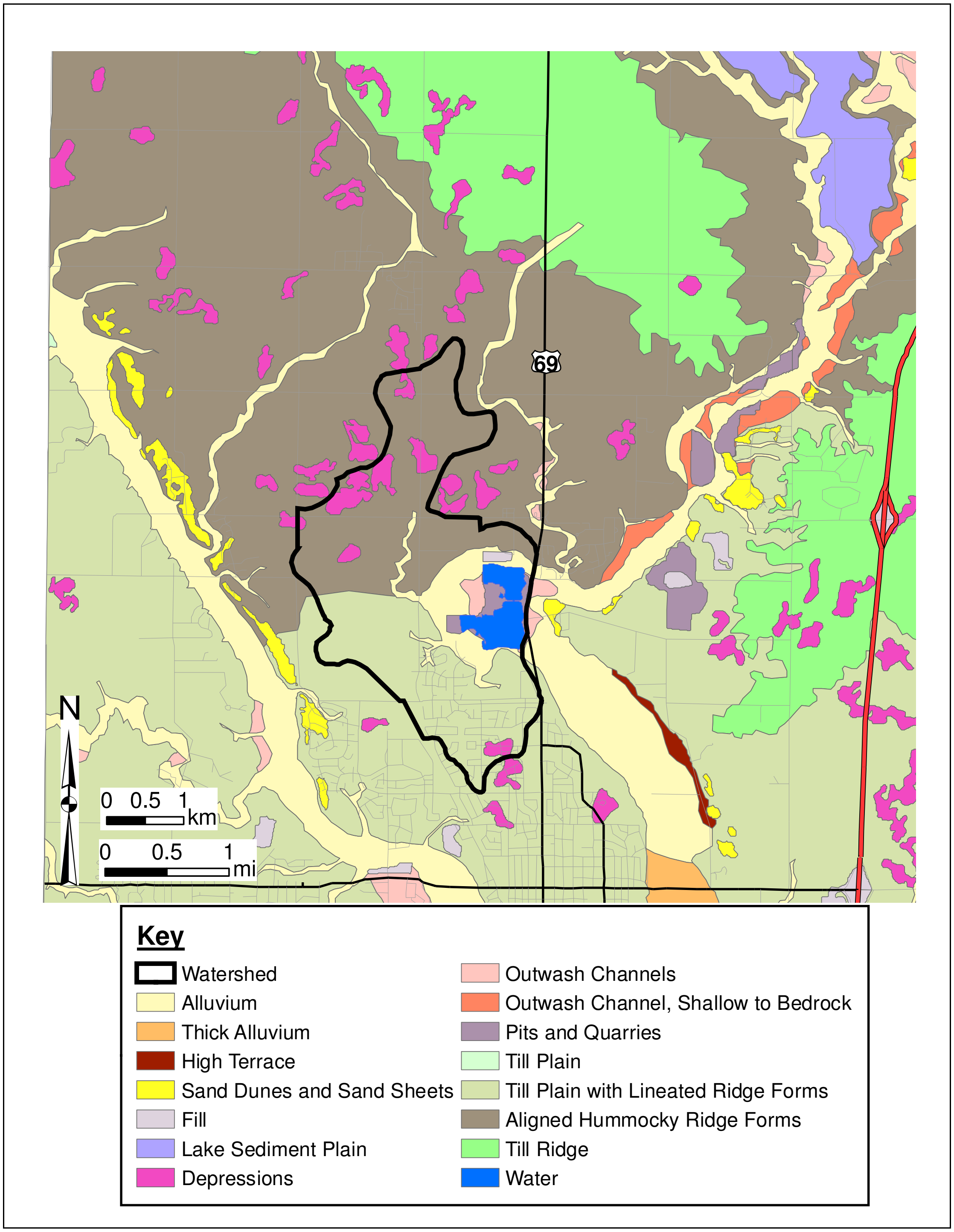


Figure 3. Surficial geology of the study area. Two predominate terrains are present: a till plain in the uplands and alluvial and outwash deposits in the lowlands of the South Skunk River valley. Adapted from Quade et al. (2001)

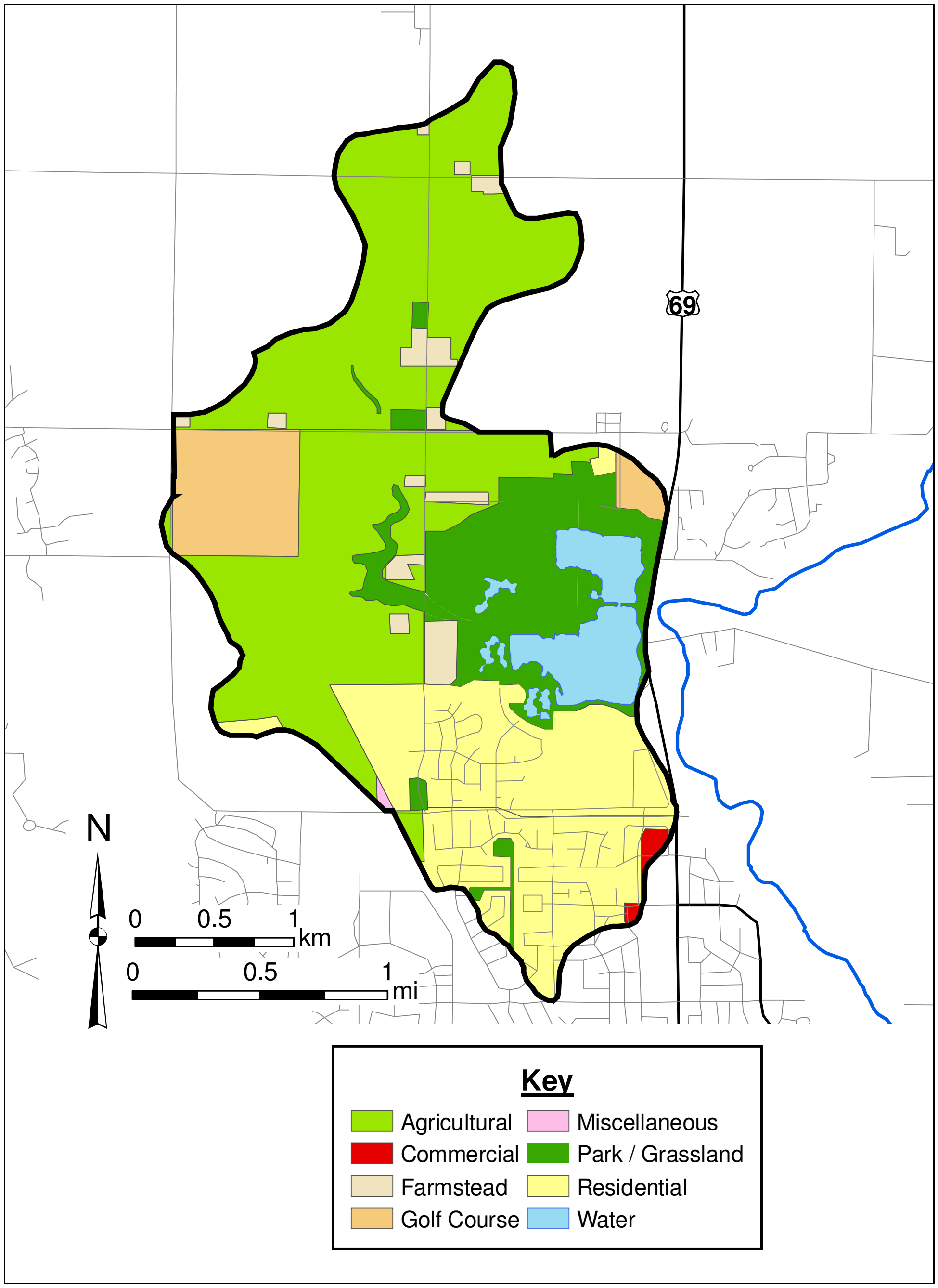


Figure 4. Land use in Ada Hayden Lake watershed. Land use is dominated by residential in the southern part of the watershed and agriculture in the northern and western parts of the watershed.

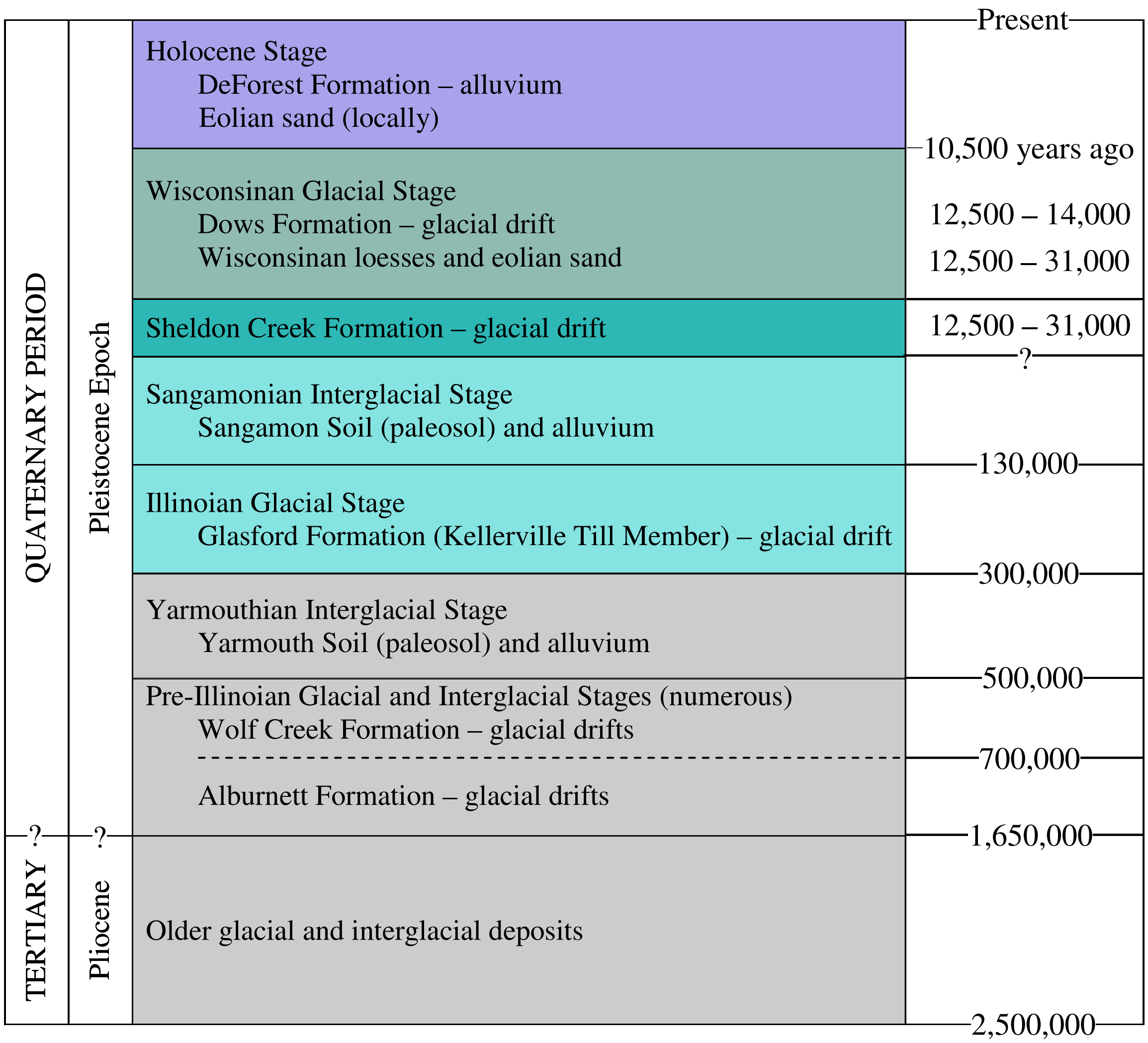


Figure 5. Quaternary stratigraphy of Iowa (adapted from Prior, 1991).

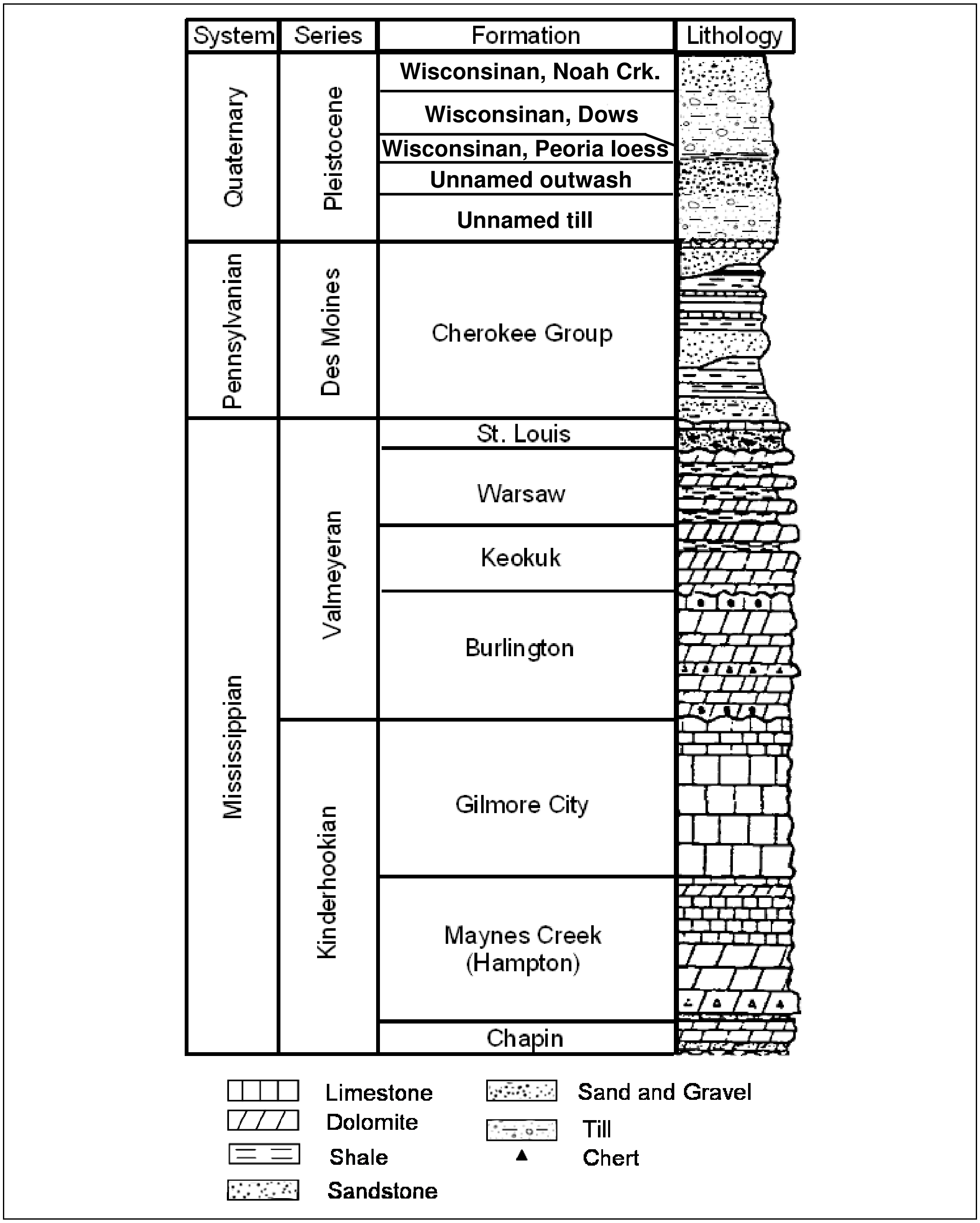


Figure 6. Stratigraphy of the Ames, Iowa area. Mississippian and Pennsylvanian age carbonates and shales underlie Pre-Illinoian and Wisconsinan till and outwash deposits (IGS, 2007b). Diagram adapted from Wille (1984).

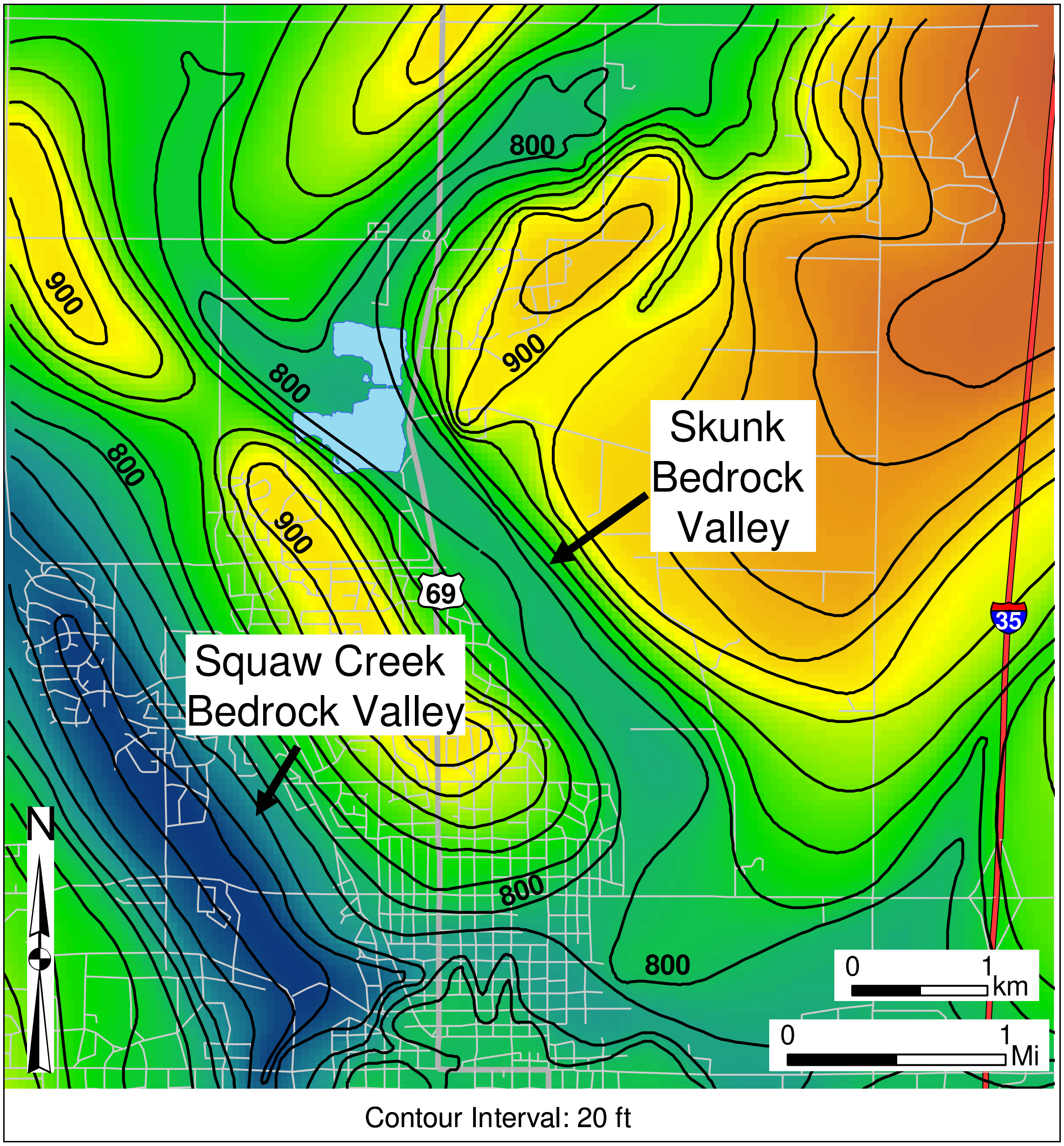


Figure 7. Bedrock topography of the Ames area. The Skunk bedrock channel runs beneath Ada Hayden Lake and plays a major role in the hydrogeology of the Ames area. Adapted from Wille (1984).

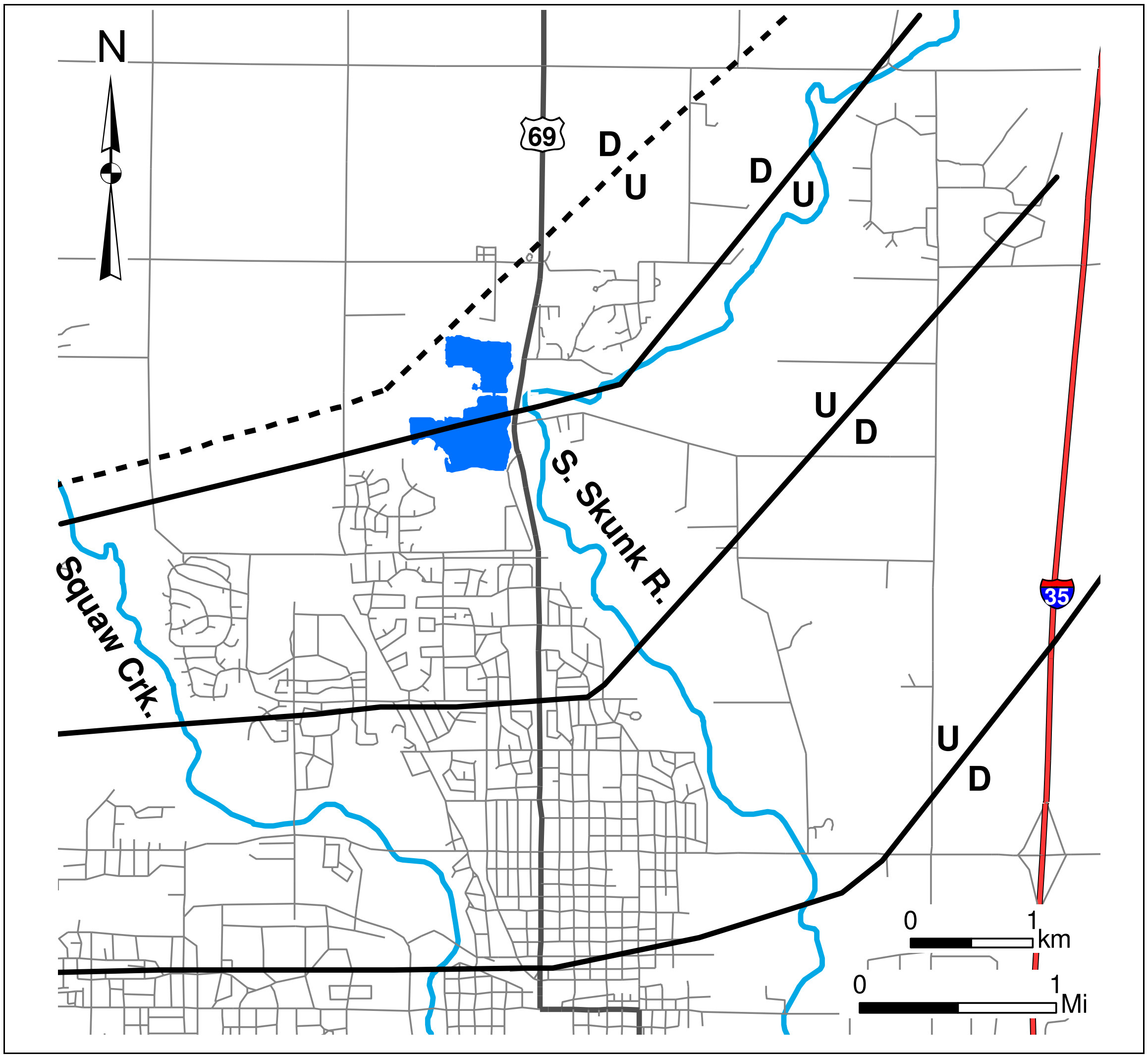


Figure 8. Location of faults in the Ames area. Several faults have been mapped with total offsets ranging from 9 to 46 m (30 to 150 ft) Dashed line indicates possible alternate location of the northern fault or an additional fault. Adapted from Wille (1984) and R. Martin (verbal comm., 2007).

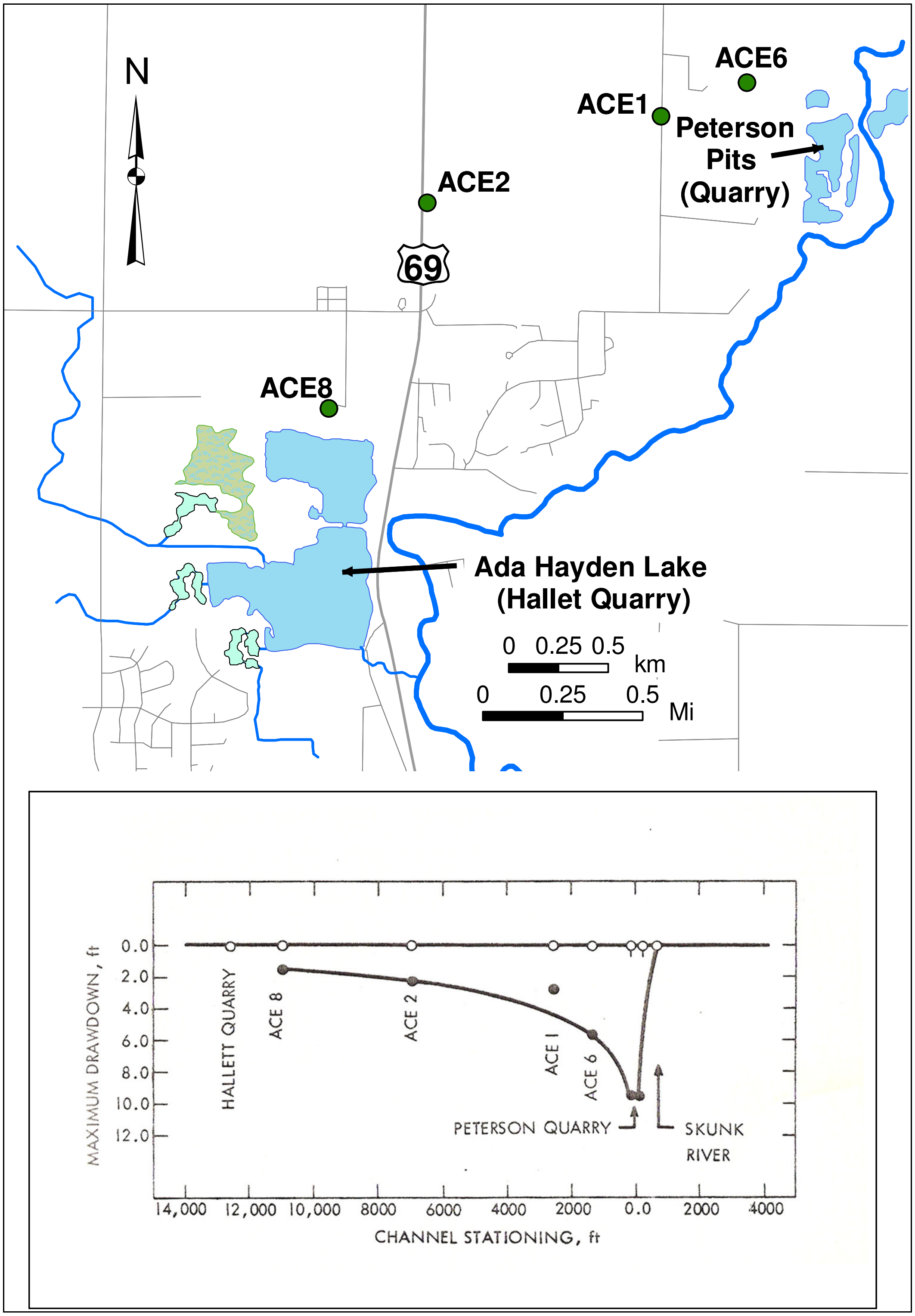


Figure 9. Drawdown observed in four monitoring wells (ACE 1,2,6, and 8) during dewatering of Peterson Pits (quarry), May 16-27, 1968.

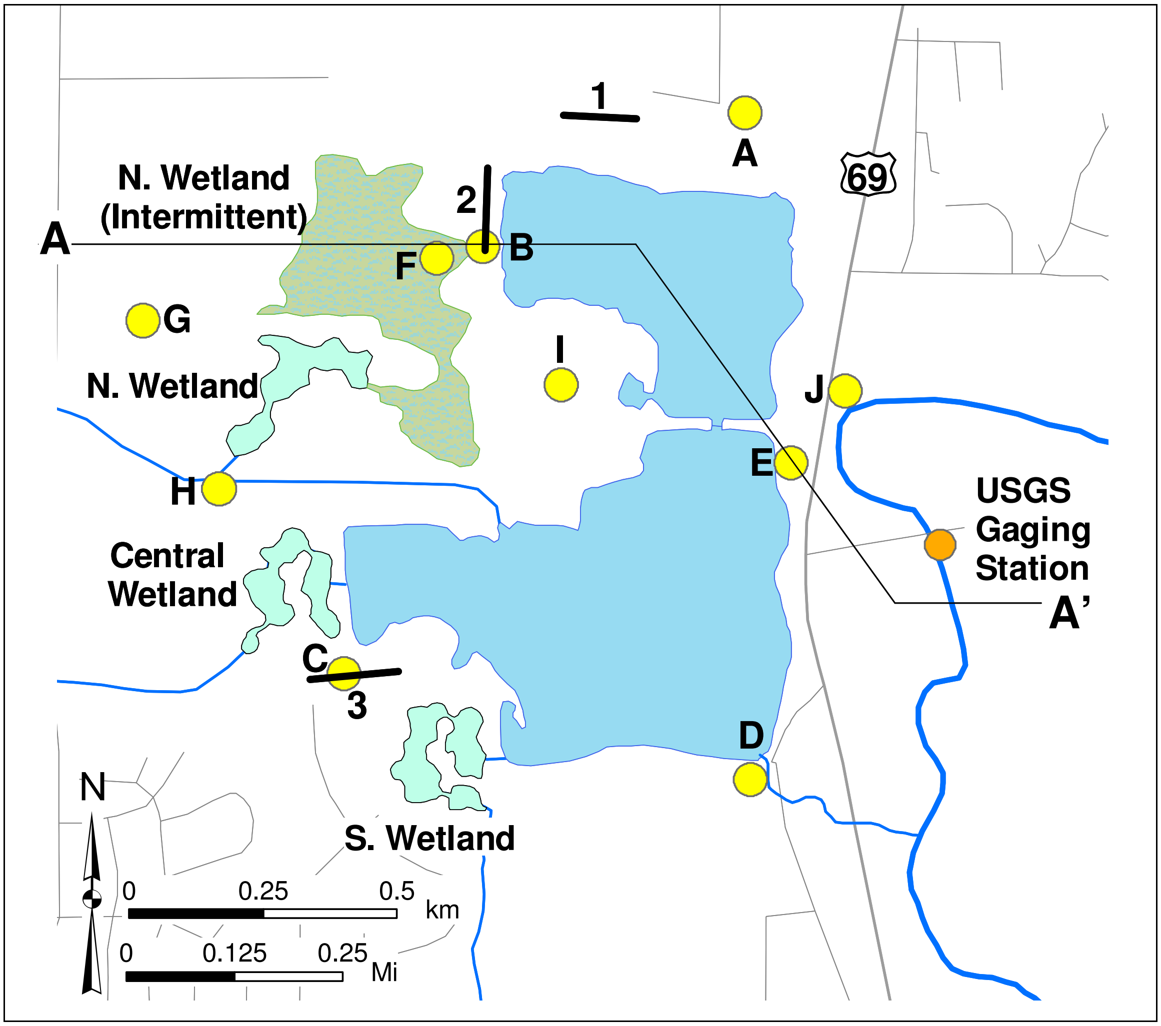


Figure 10. Location of piezometers, seismic lines, and wetlands adjacent to Ada Hayden Lake. Yellow dots with letters indicate piezometer nests. Black lines with numbers indicate locations of seismic lines (see Figure 12). Orange dot is the location of USGS gaging station on the South Skunk River (05470000). Line A to A' is location of cross section for Figure 13.

Figure 11. Photo looking north showing the approximate location of the three separate lake basins that existed at Hallett's Quarry at time of 1976-77 drought. Highway 69 is located on the east side of the lake (photo from Antosch, 1982).

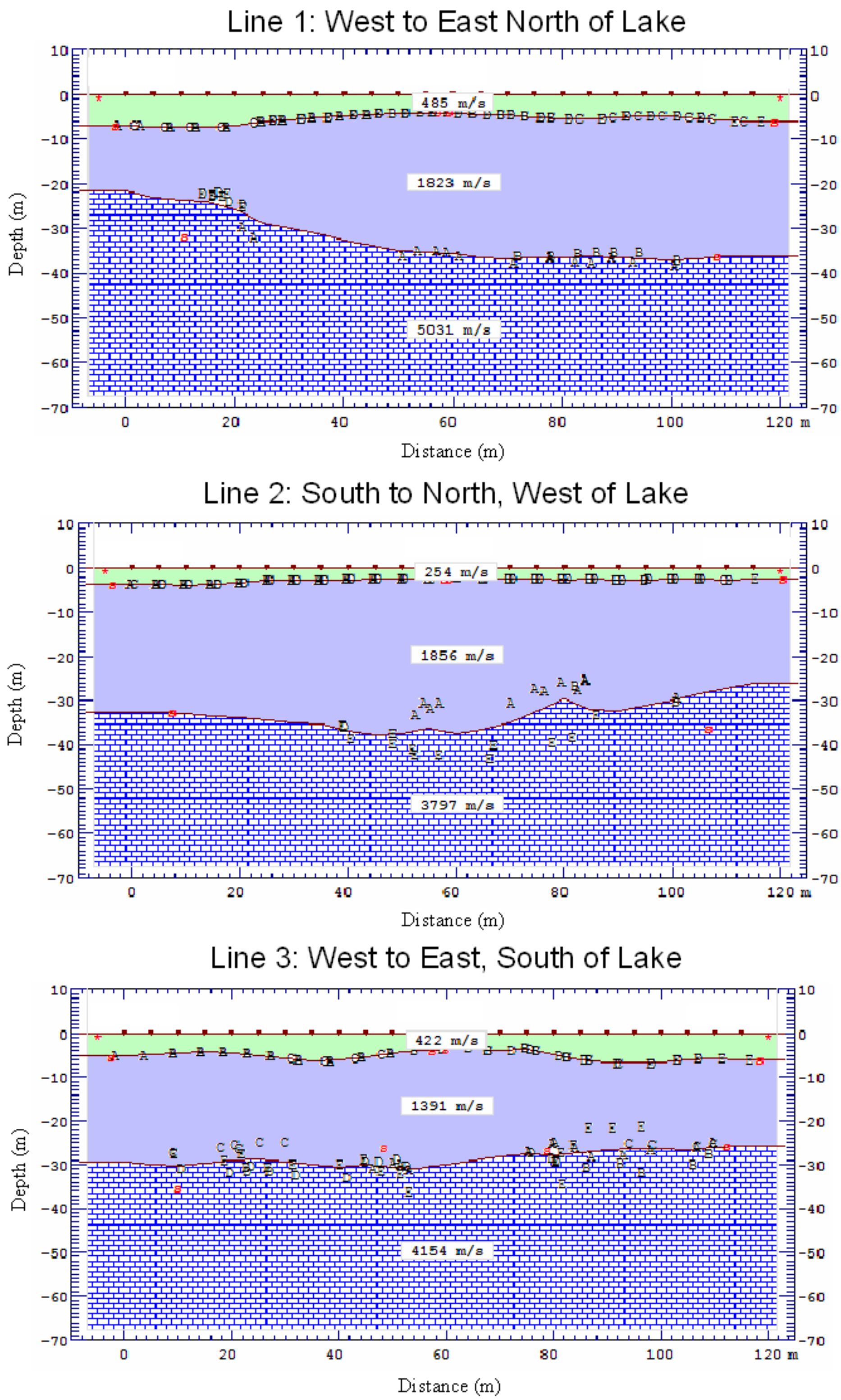


Figure 12. Results of seismic refraction study showing three velocity layers with depth. Seismic velocities shown in m/s. Layer description in text.

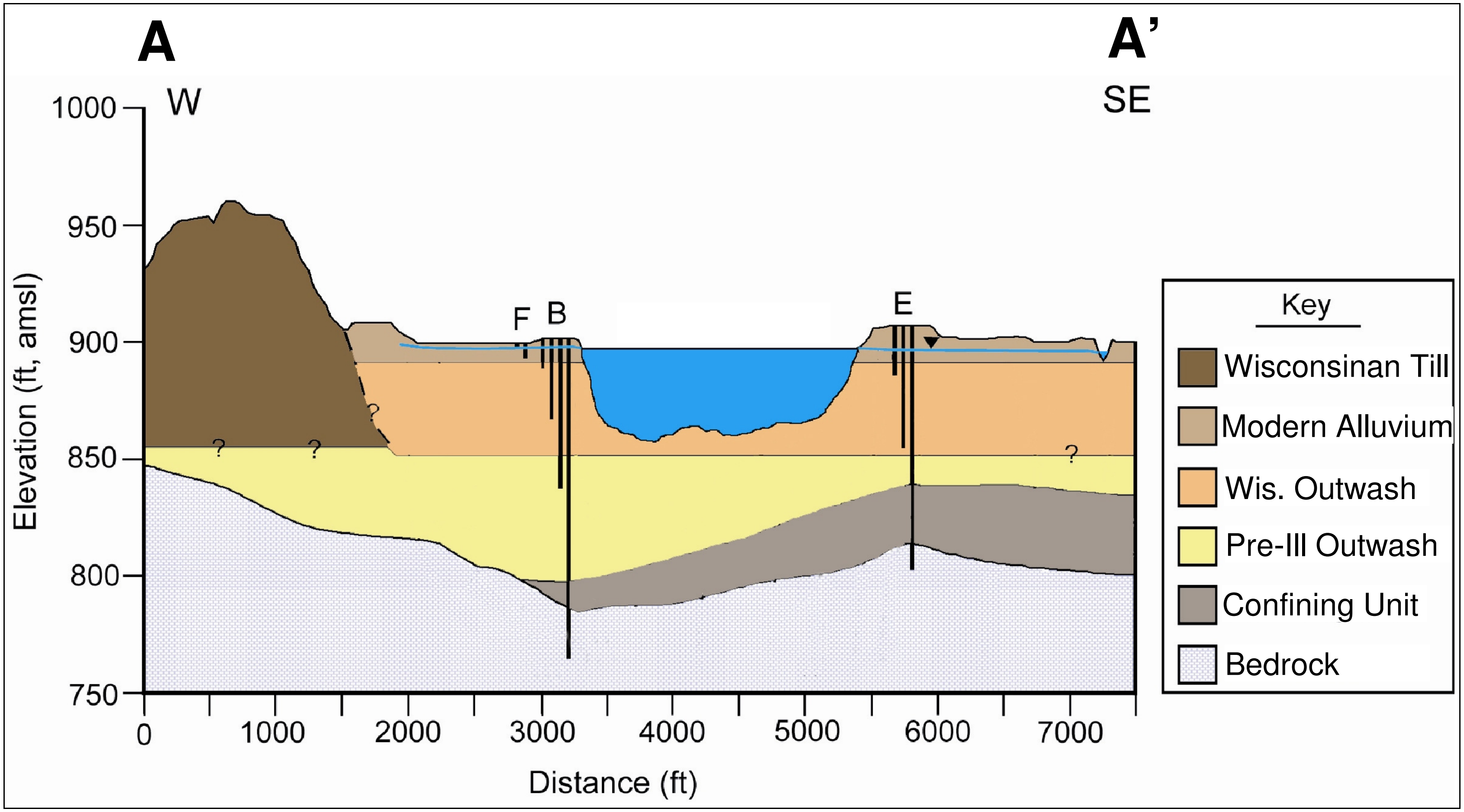


Figure 13. General west-to-east cross section through Ada Hayden Lake based on drilling in this study. Piezometers in nests B and E shown with vertical black line. Confining unit may be an older till and/or loess. Line of section in Figure 10.

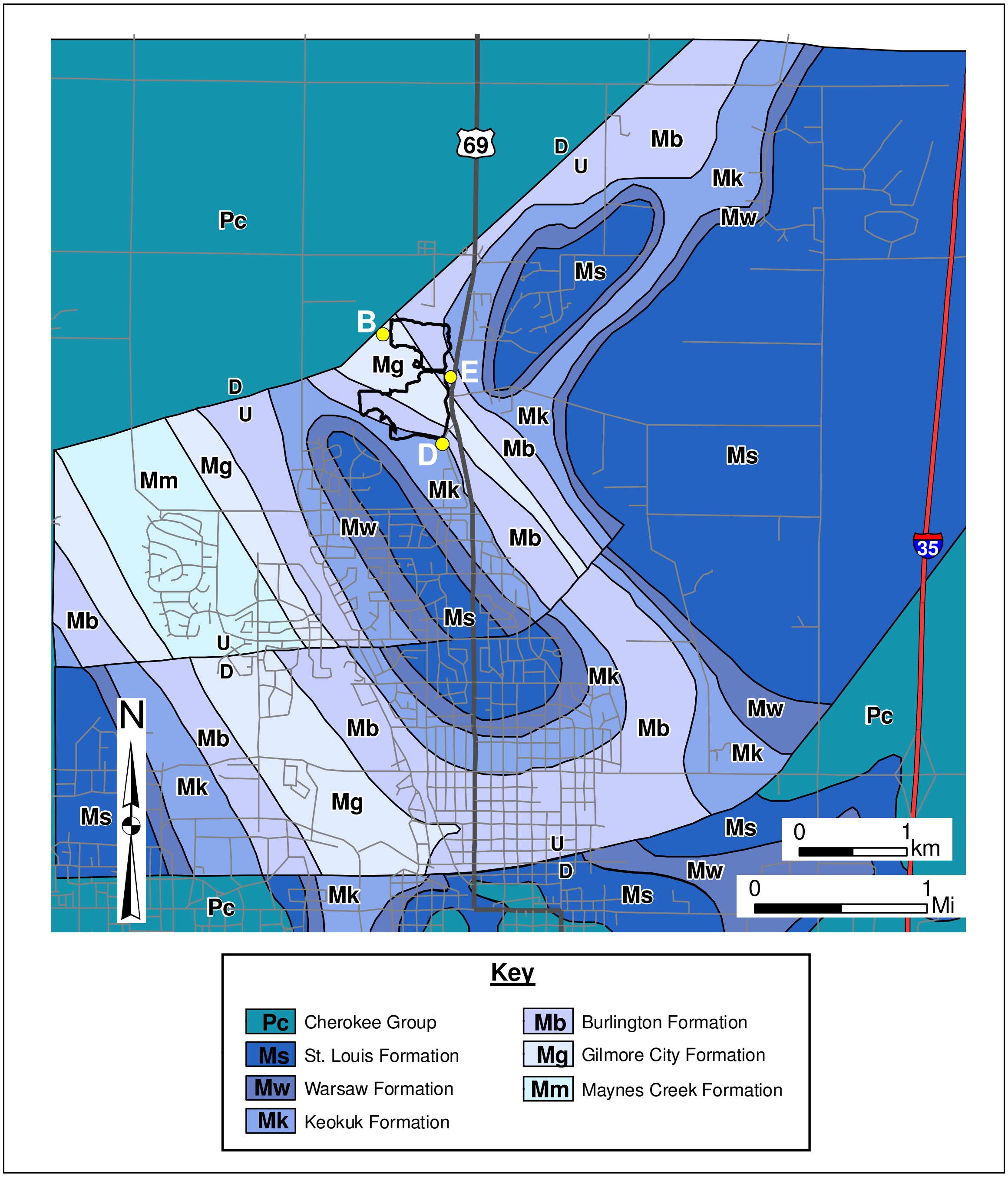


Figure 14. Bedrock geology of the Ames area including lithologic interpretations of the bedrock at Ada Hayden Lake from piezometer nests B, D, and E (in yellow). P = Pennsylvanian, M = Mississippian. Location of the faults is not well known. Modified from Wille (1984).

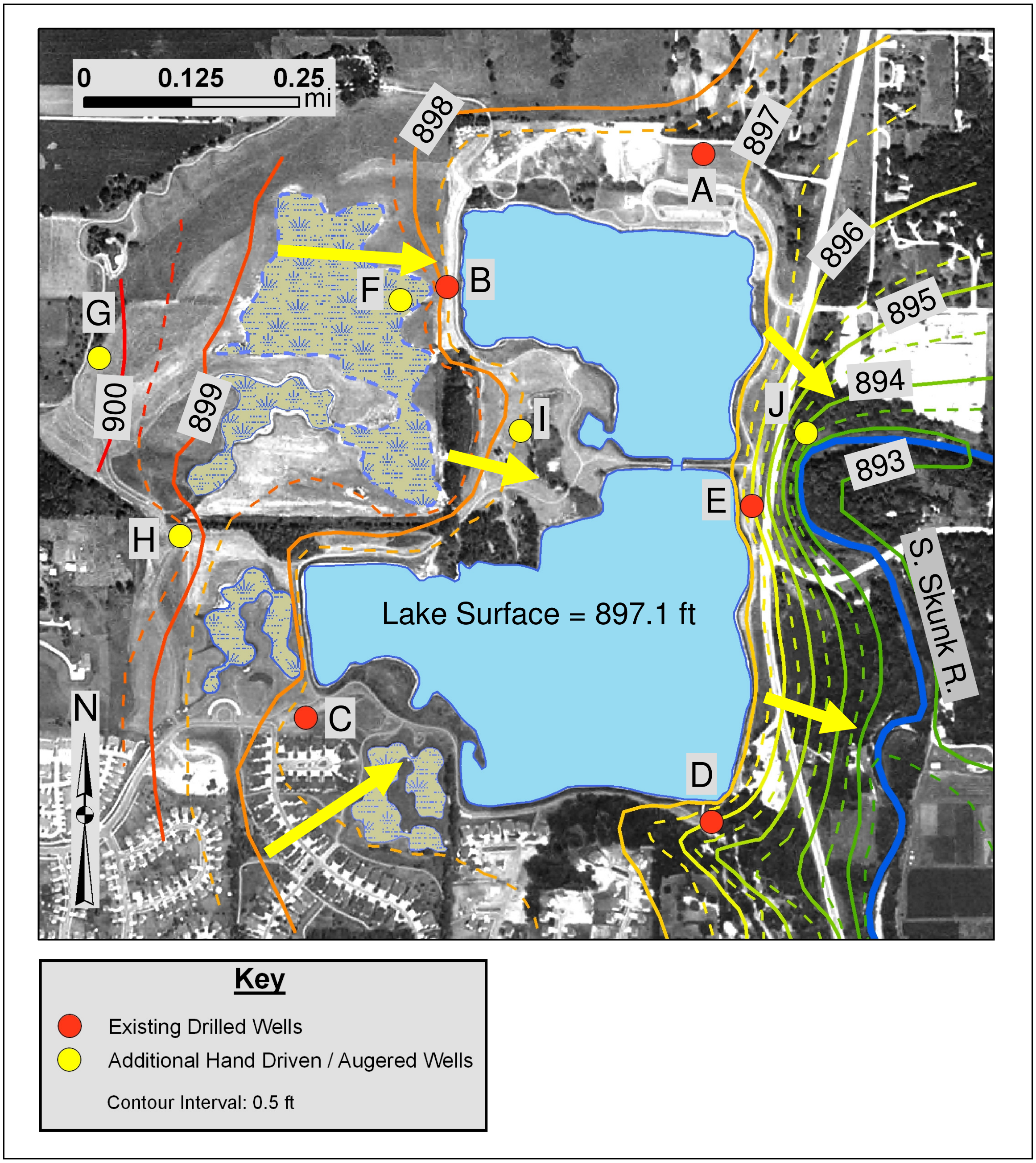


Figure 15. Contour map of water table surface from December 2006. Groundwater flows into the lake from the north, west, and southwest. Groundwater flows out of the lake to the east and southeast and into the South Skunk River.

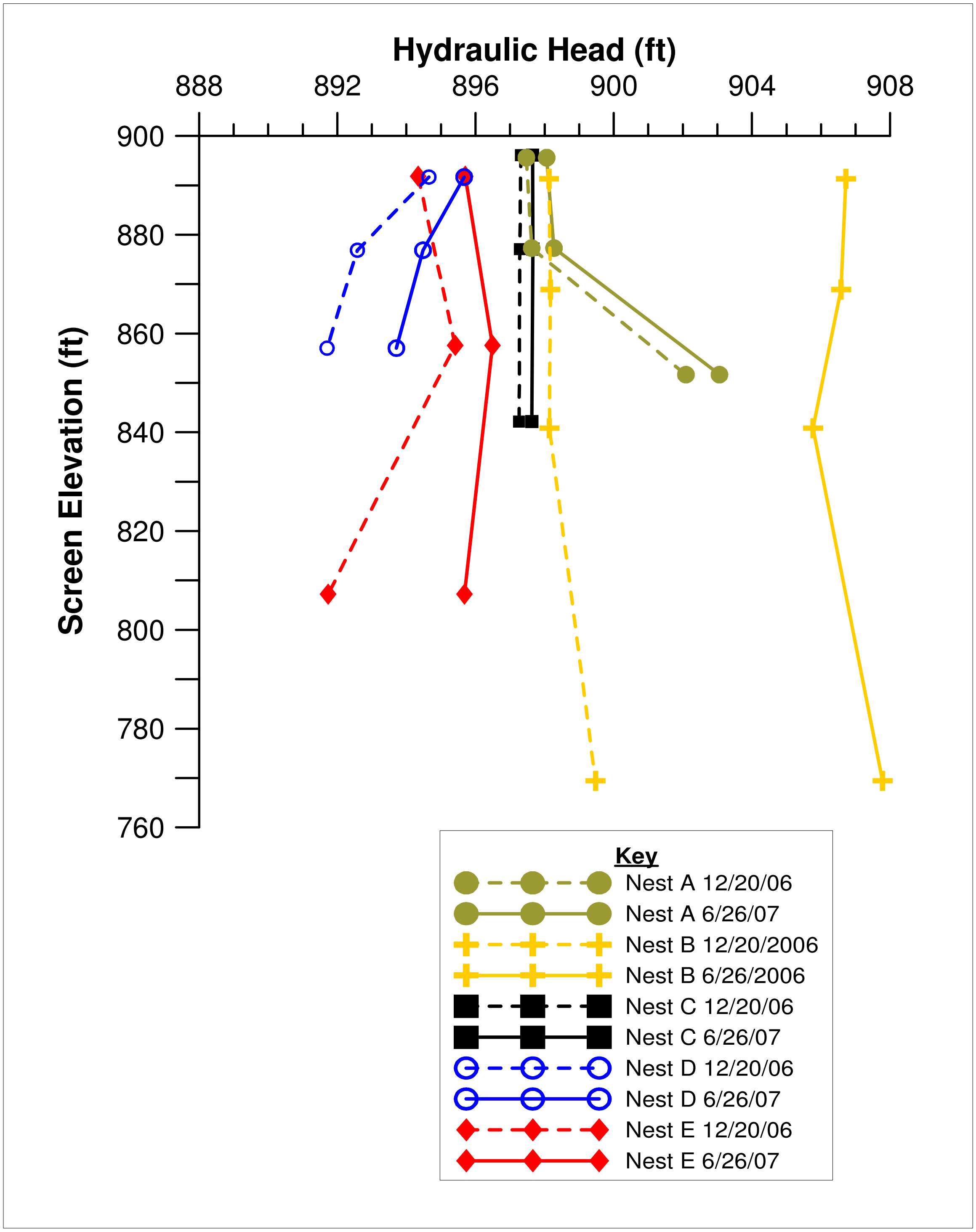


Figure 16. Profile of hydraulic head with depth at piezometer nests A to E. The Y axis is the screen midpoint.

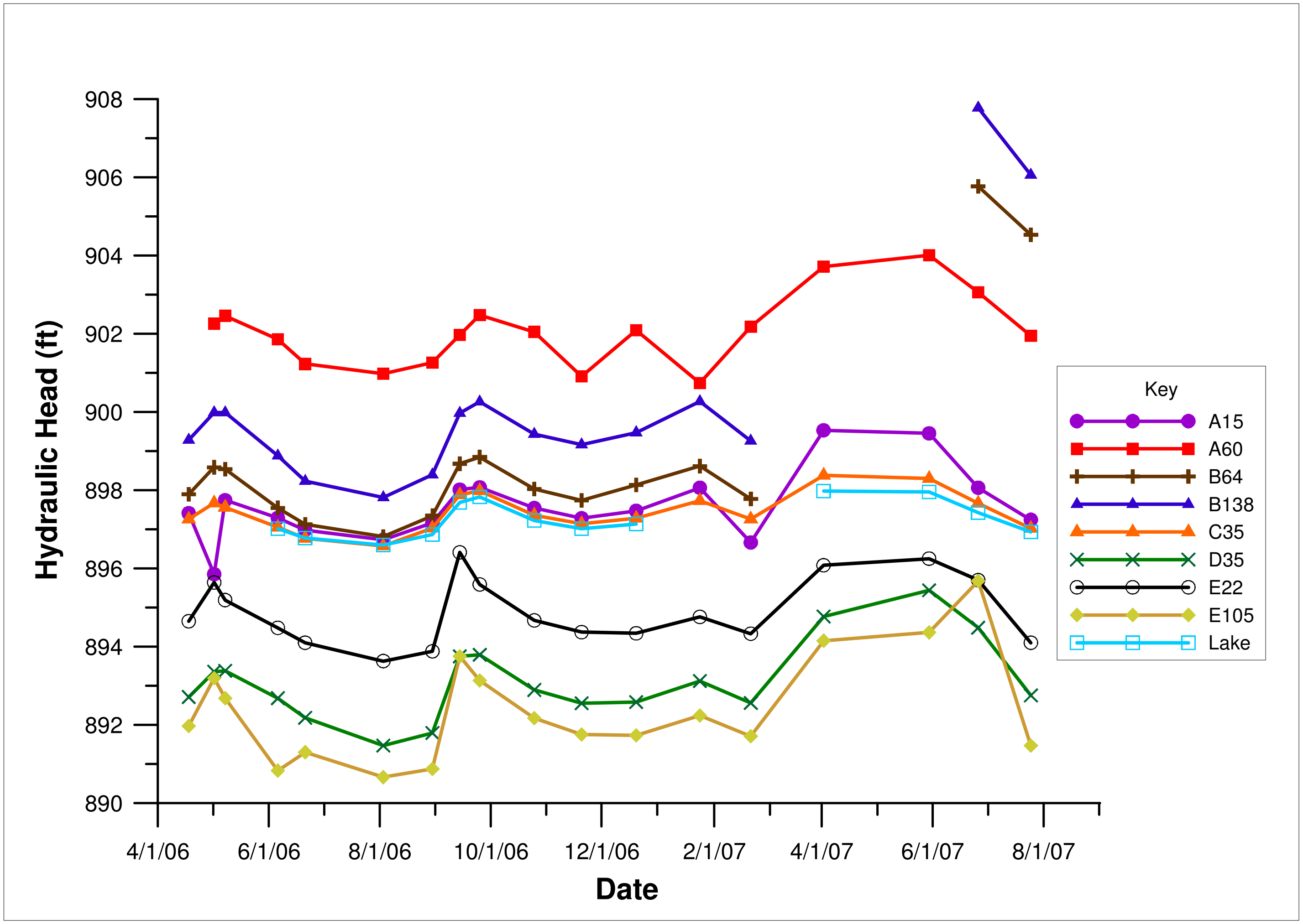


Figure 17. Hydrograph of hydraulic head values from selected piezometers showing relationships of head to lake levels. Heads at piezometer nest B were not measured during April and June of 2007 due to flooding of the northern wetland.

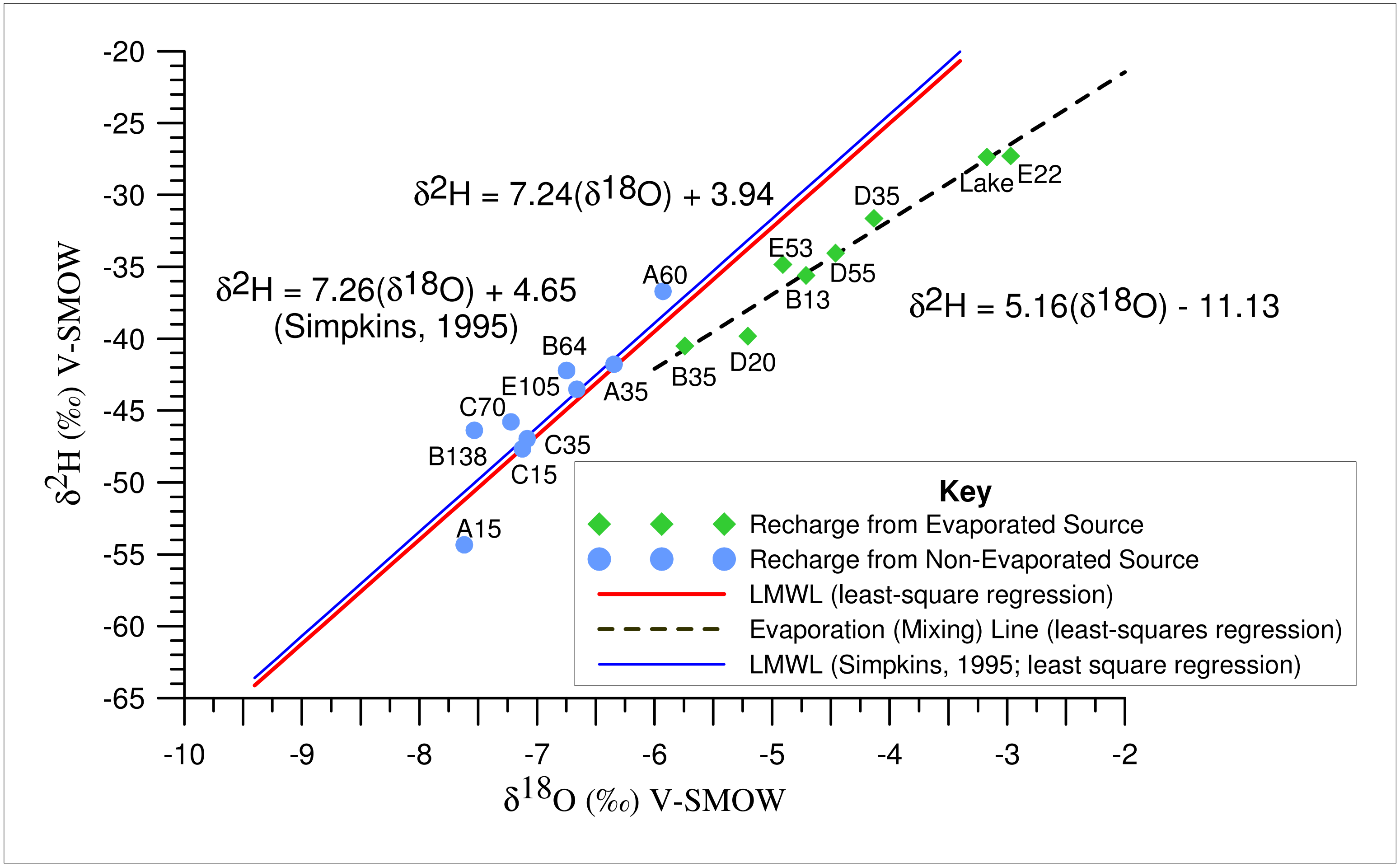


Figure 18. Plot of $\delta^{18}O$ vs. δ^2H for groundwater and lake samples. Meteoric water line and equation shown for this study and precipitation data in Simpkins (1995). Groundwater on the down-gradient, eastern side of the lake shows an evaporative signature indicating the lake as a source of water. Shallow groundwater near the northern wetland also shows an evaporative signature indicating that water in the wetland is recharging the aquifer and flowing to the lake as groundwater.

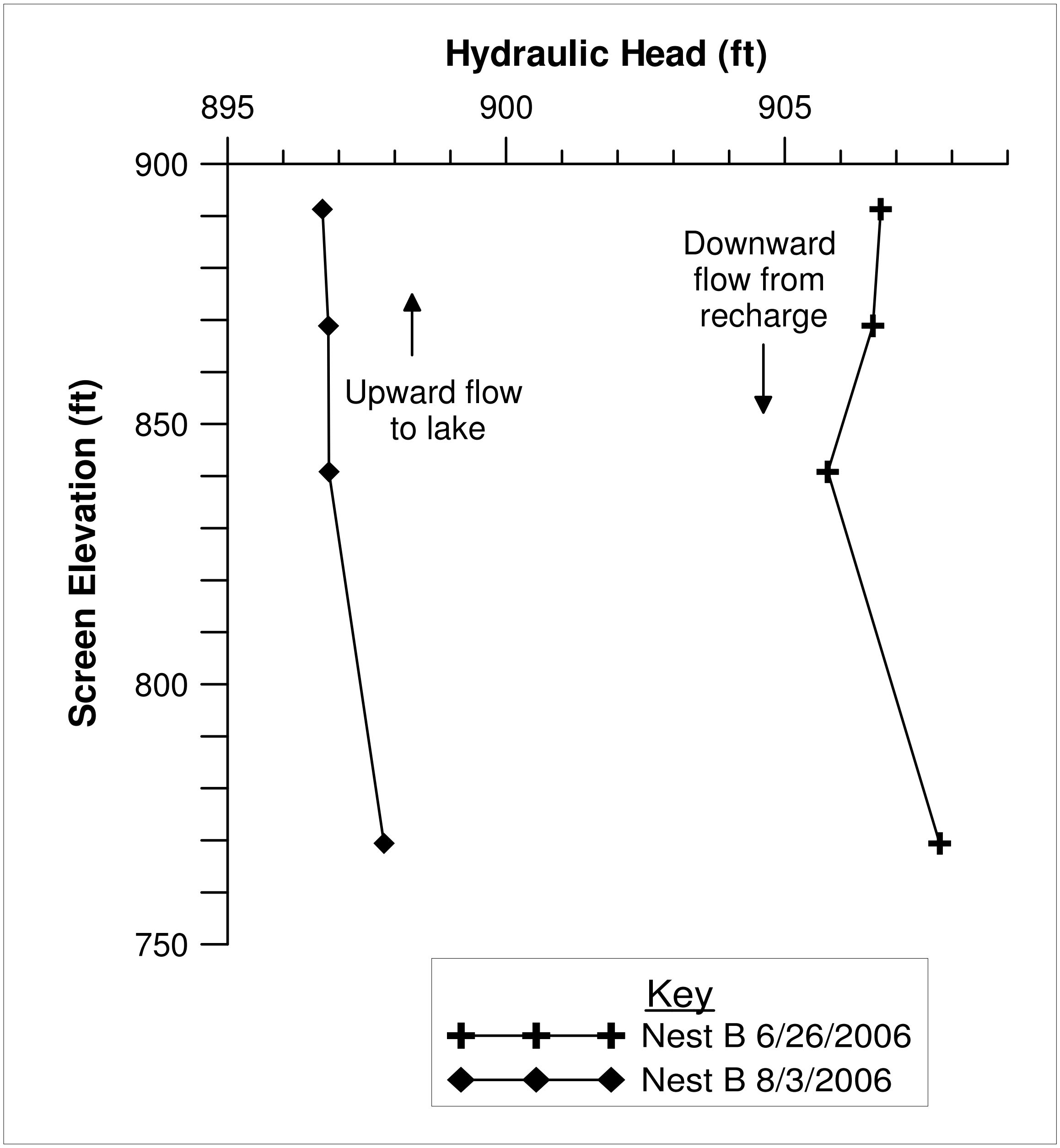


Figure 19. Hydraulic head with depth at nest B showing a reversal of the vertical gradient at shallow depths. On 8/3/2006 the northern wetland complex was dry and flow was upward to the lake. On 6/26/2007 the northern wetland was flooded and flow was downward.

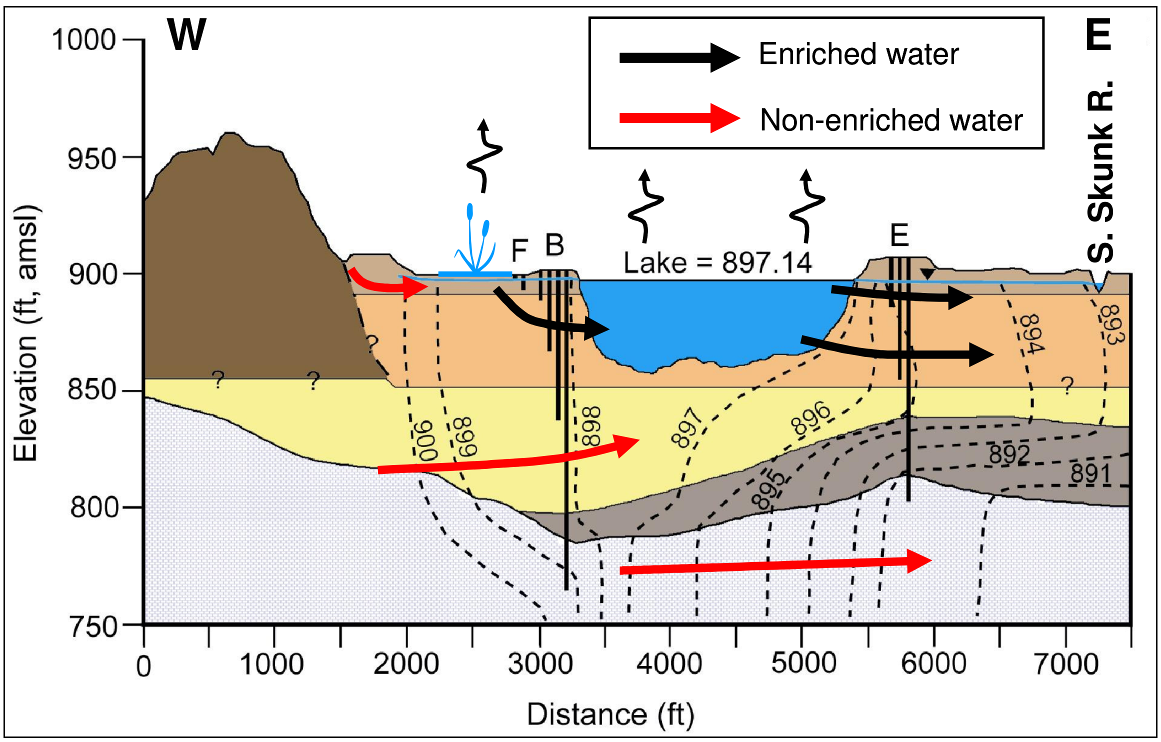


Figure 20. Conceptual representation of groundwater flow based on stable isotope and hydraulic head data. Based on Section A-A' (Figure 13).

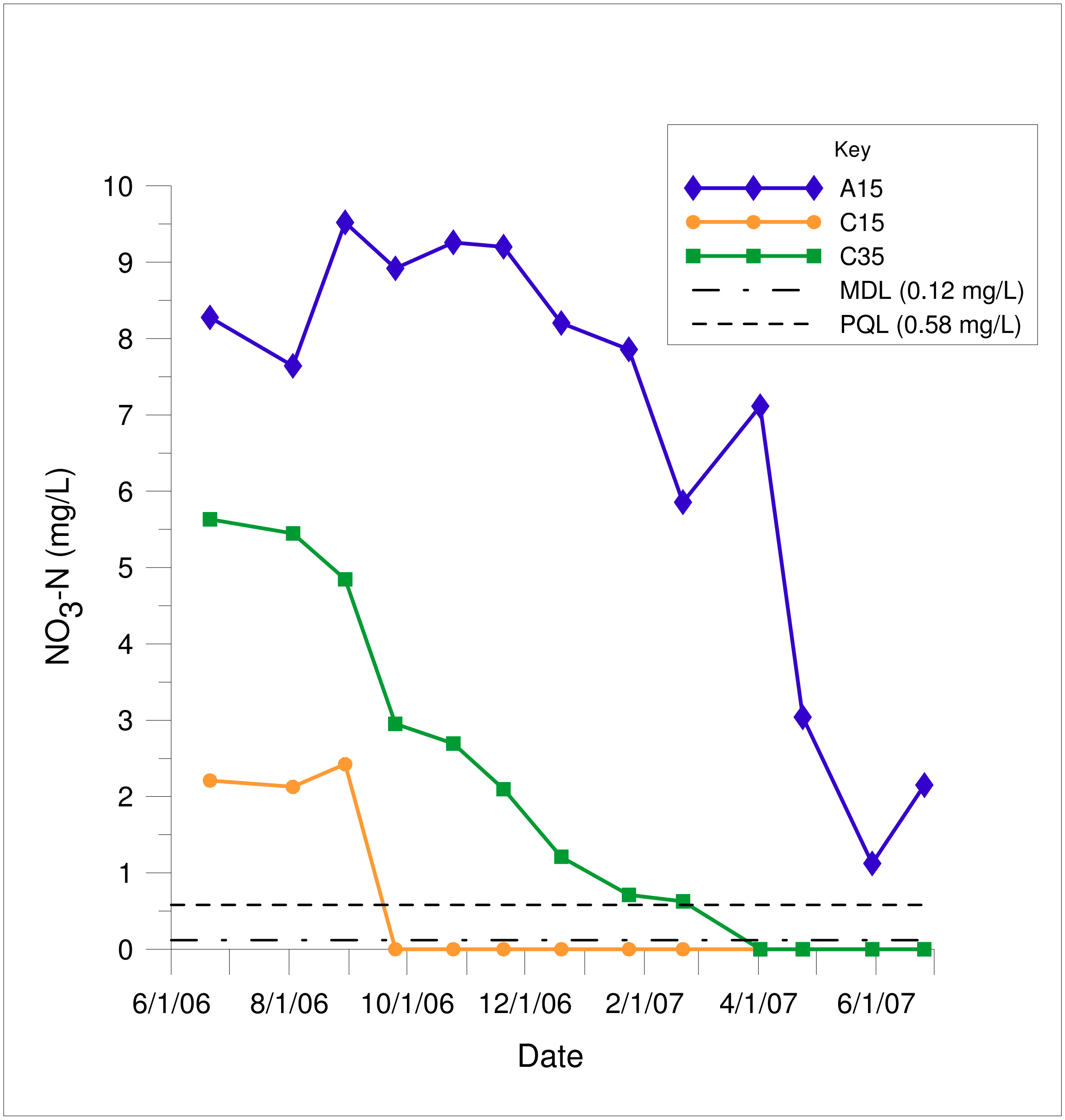


Figure 21. Nitrate-N concentration trends in groundwater from shallow piezometers at nests A and C.

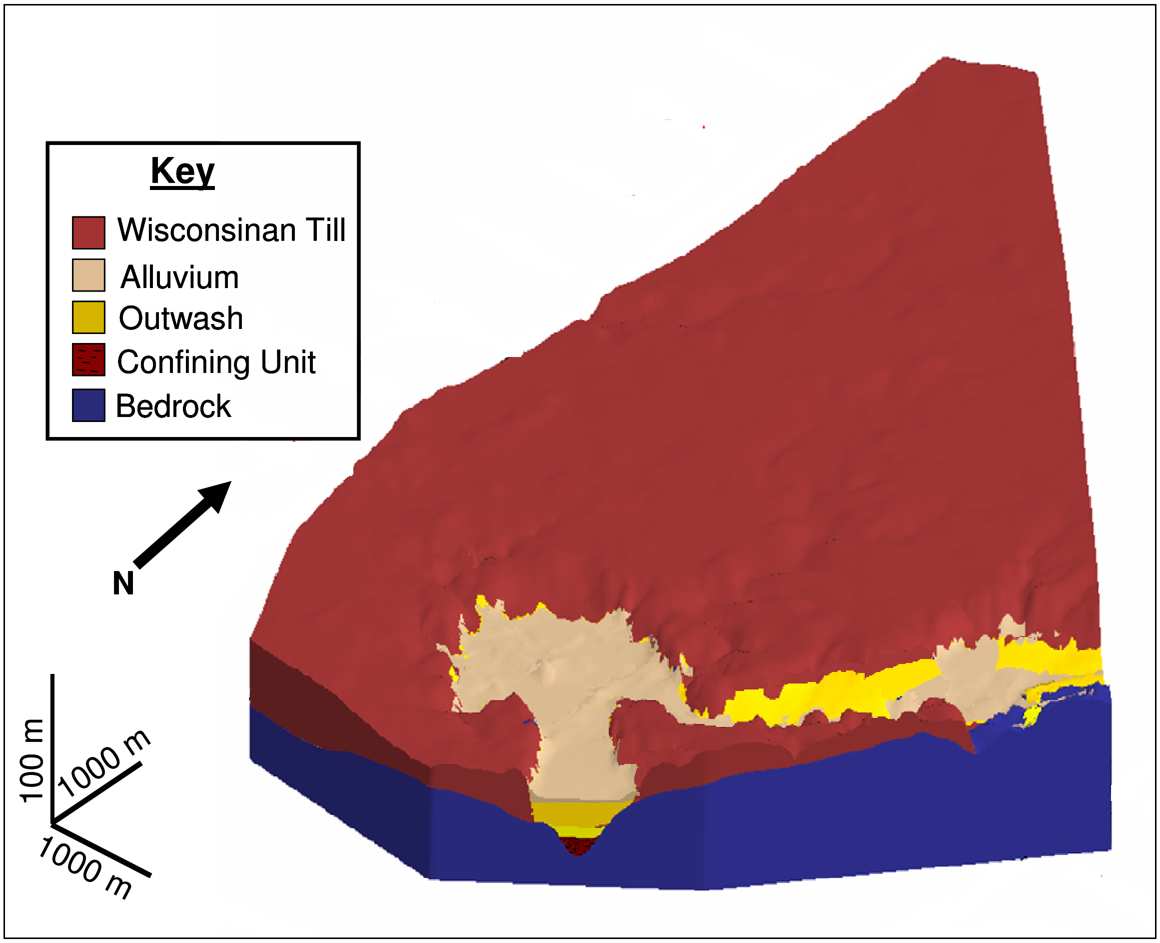


Figure 22. A 3-D representation of stratigraphy in the model domain based on 3-D solids modeling in GMS.

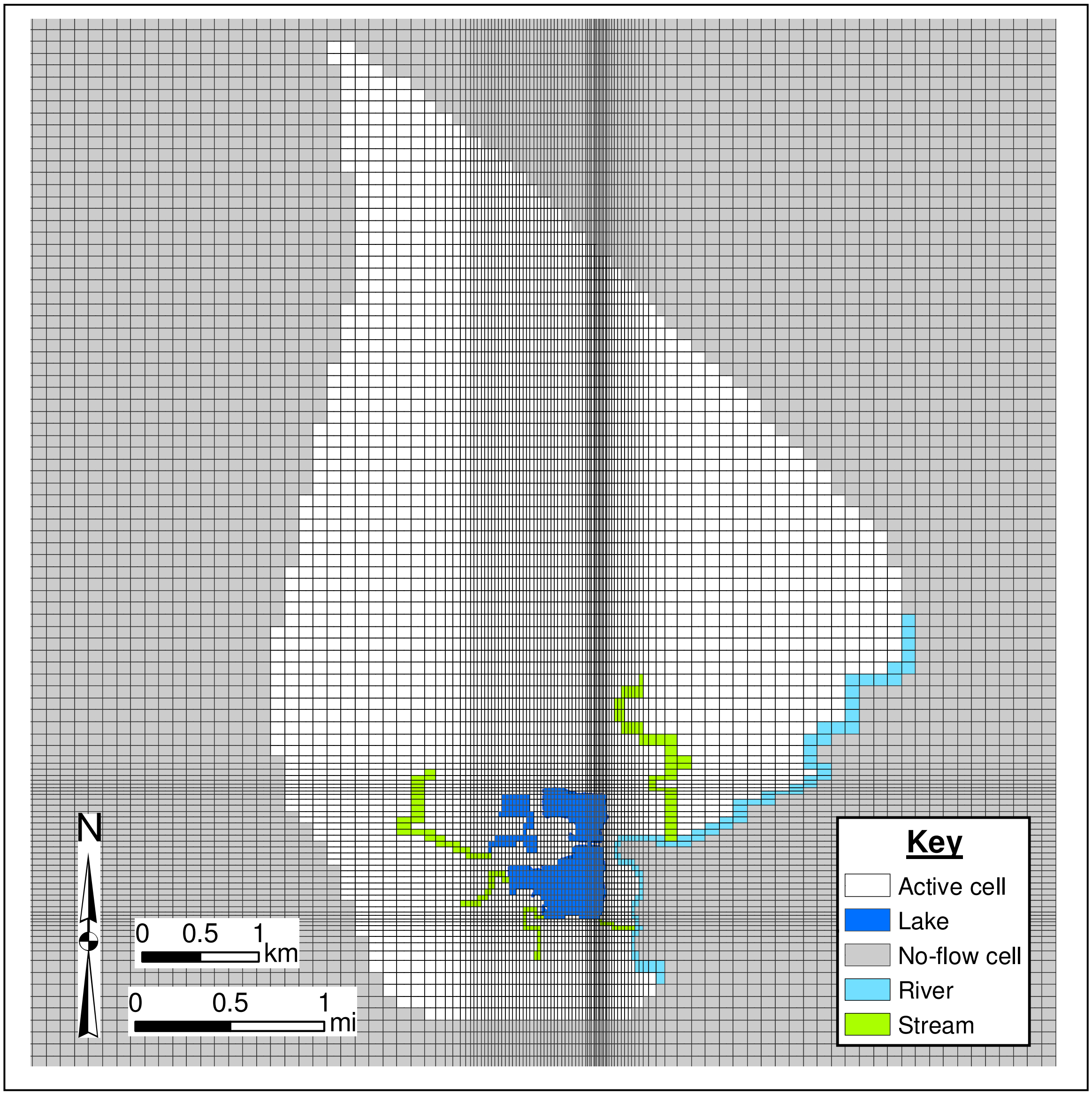


Figure 23. Finite-difference grid for the model. Dark area near the lake represents a decrease in grid spacing to accommodate steep hydraulic gradients at the east side of the lake.

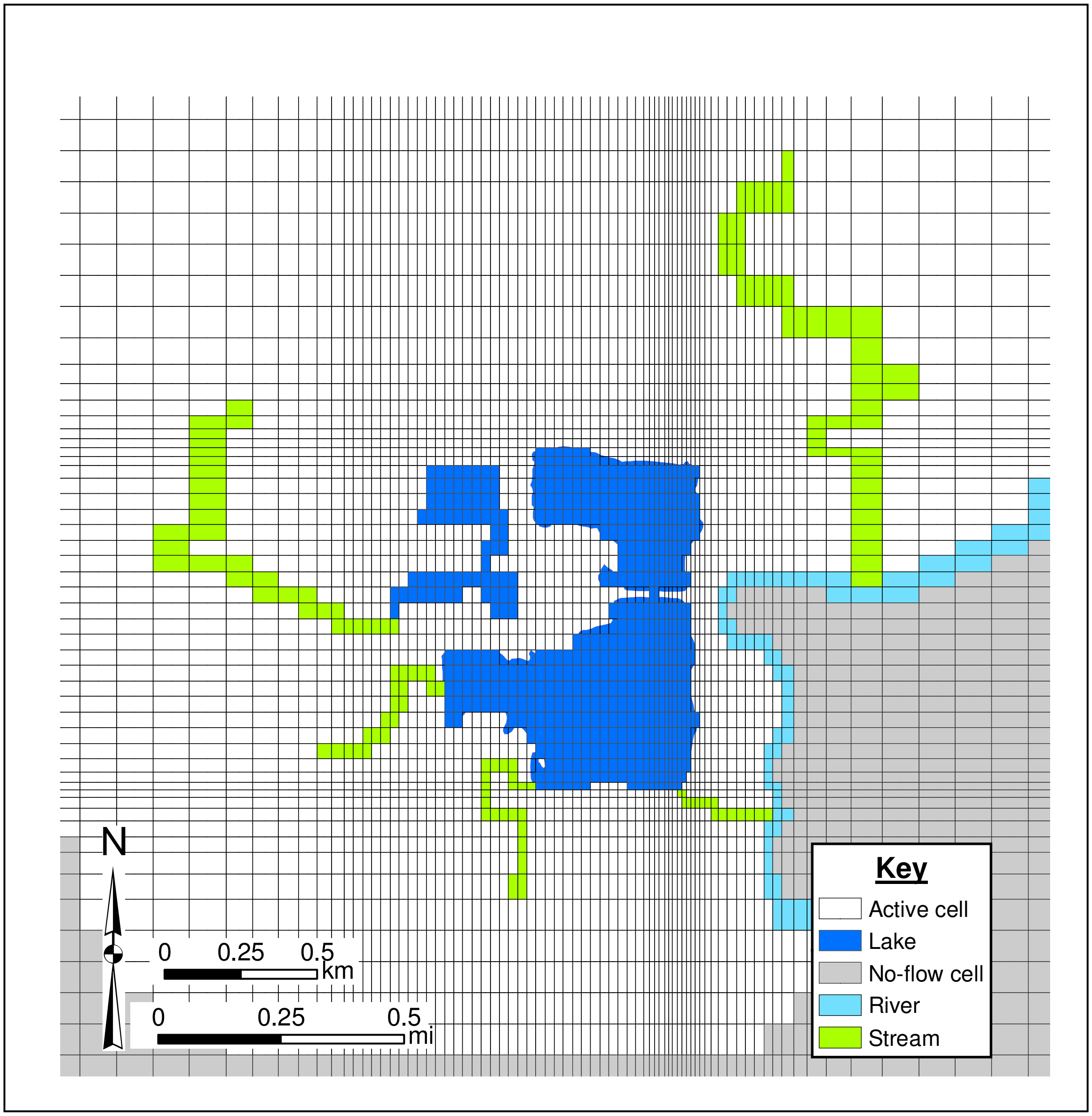


Figure 24. Enlarged view of finite-difference grid for the 3-D groundwater model (see Figure 23).

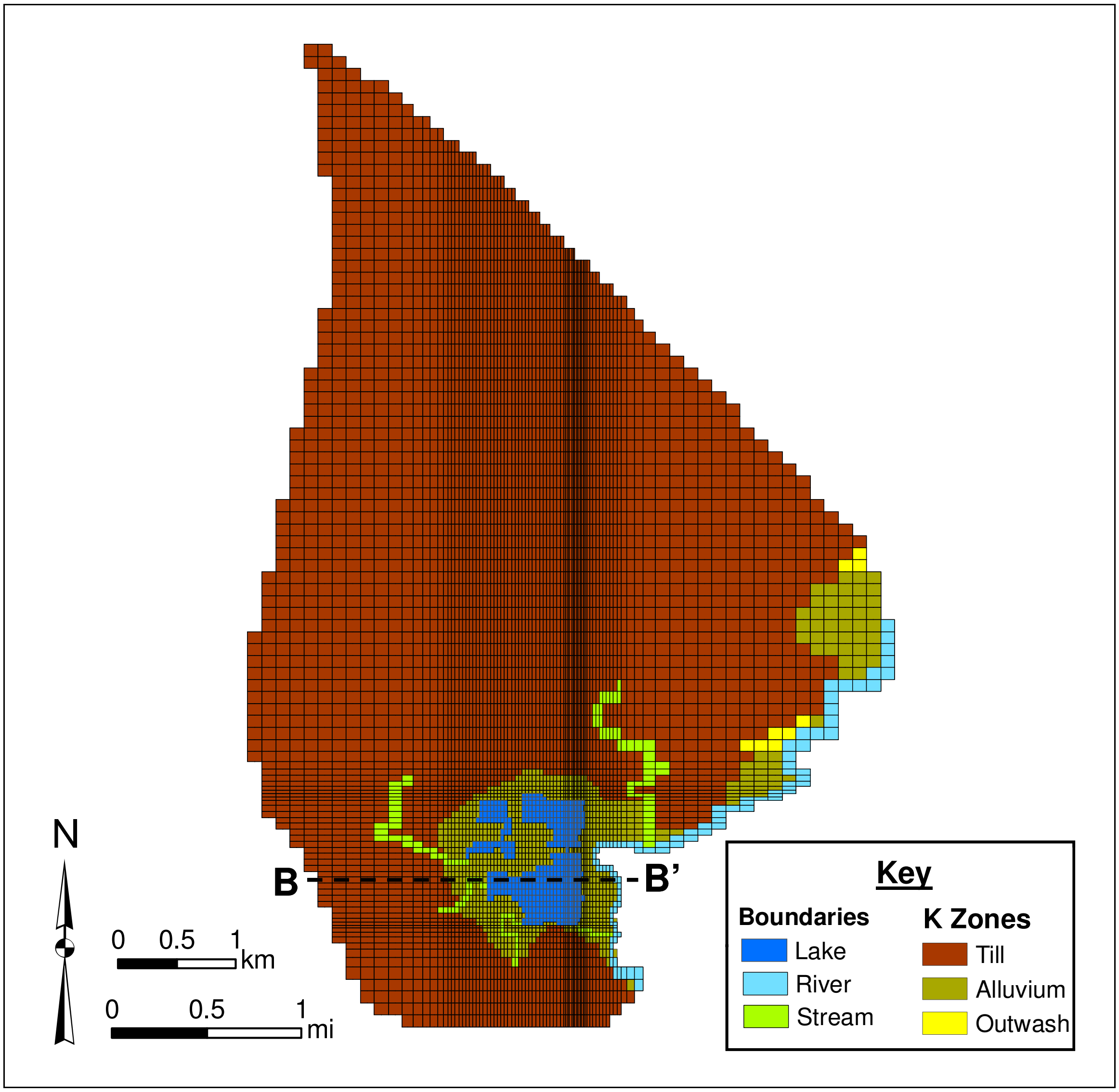


Figure 25. Model K zones and boundaries at the top of the model. Dashed line indicates location of cross section shown in Figure 27.

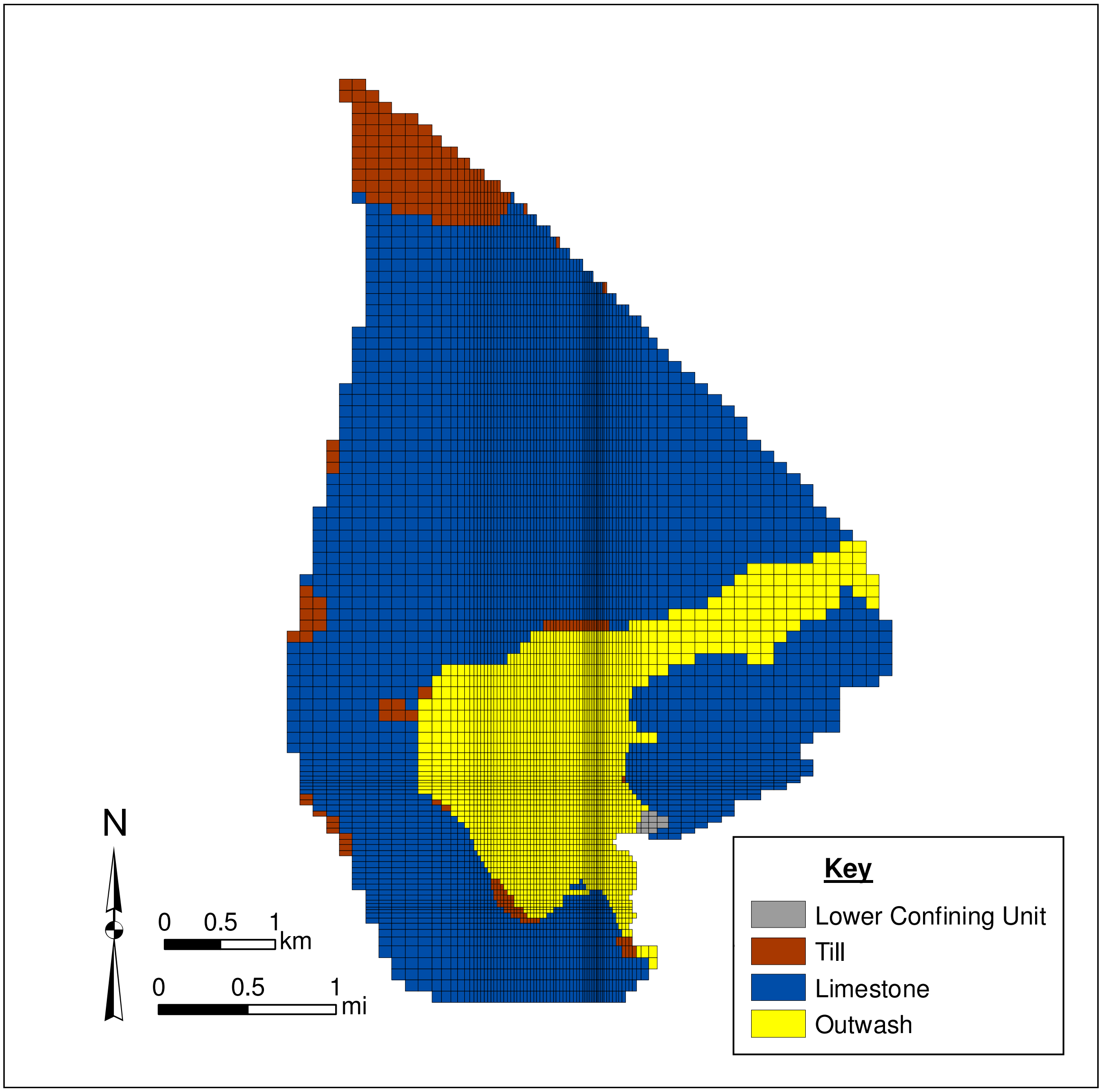


Figure 26. Cutaway view showing K zones in layer 5 of the model. Outwash (yellow) within the Skunk bedrock valley trends to the north and east from the lake.

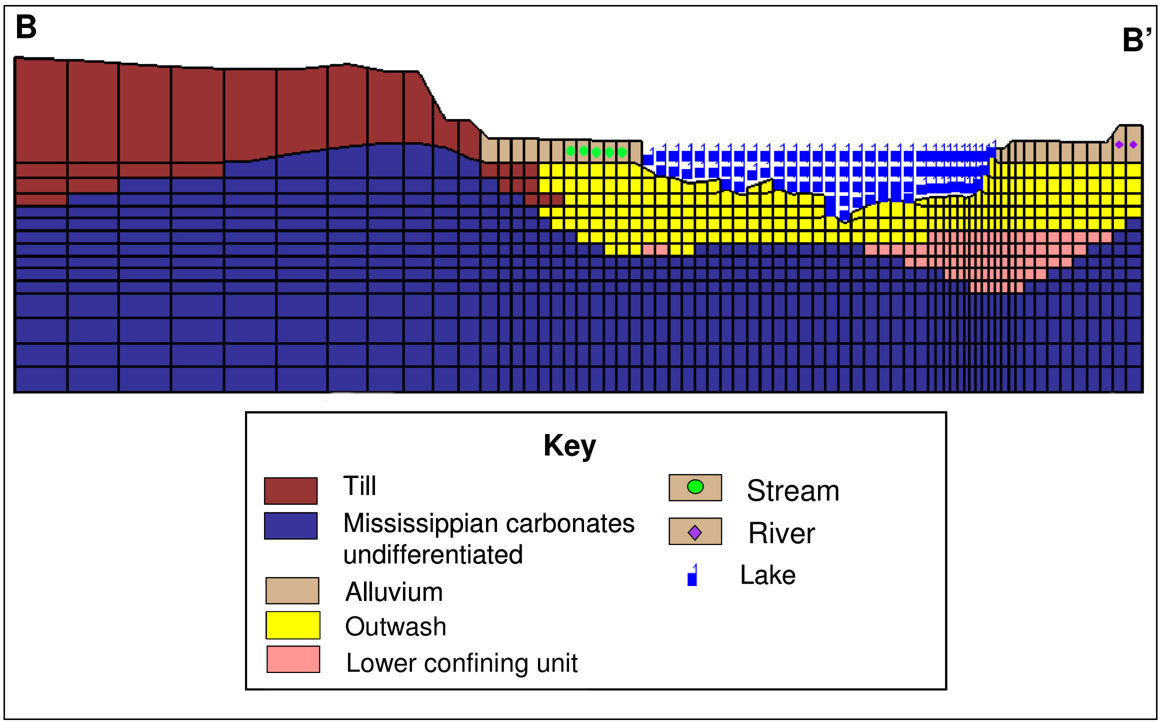


Figure 27. West to east **c**ross section through row 99 of model showing major hydrostratigraphic units present in the subsurface at Ada Hayden Park. Line of section shown in Figure 25.

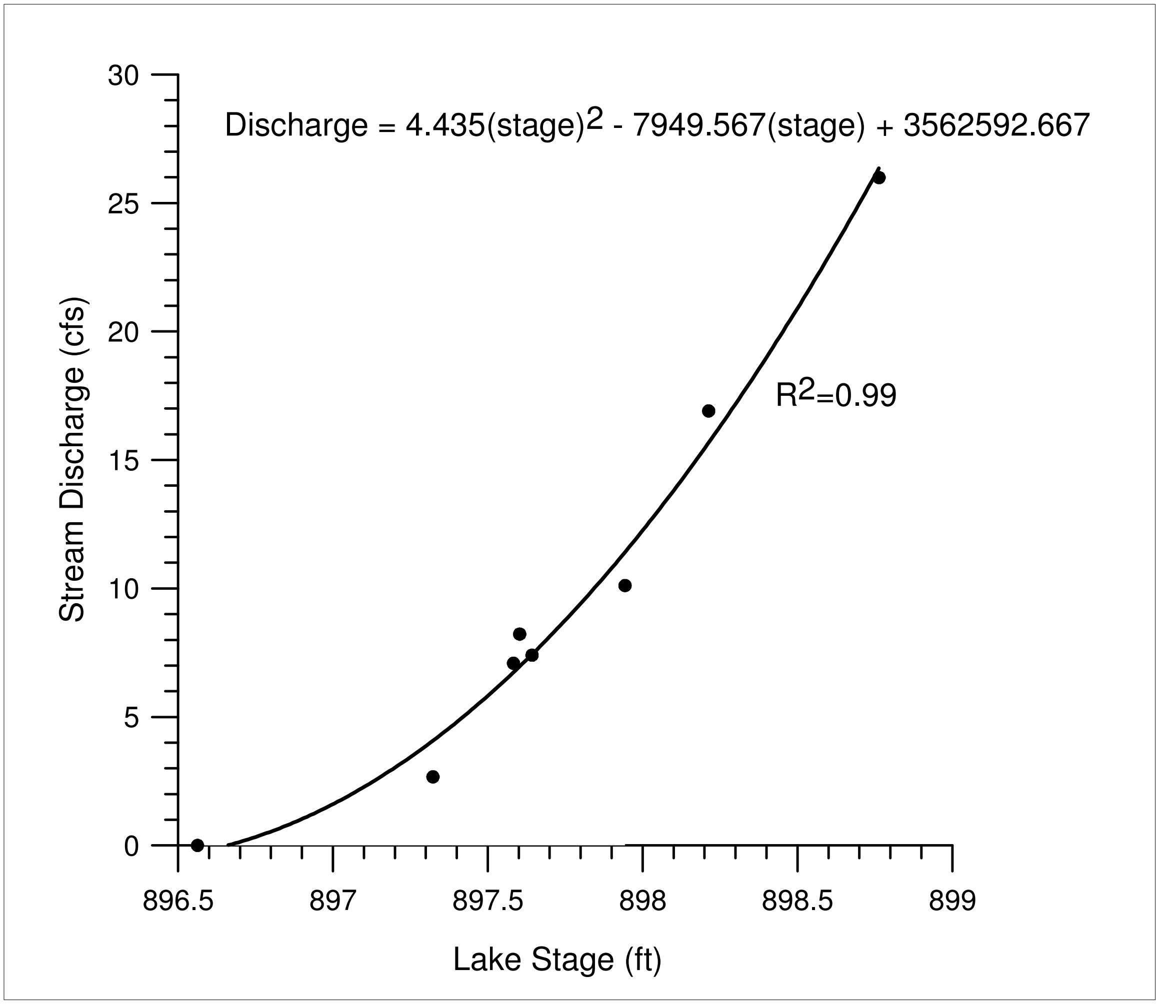


Figure 28. Rating curve of lake stage vs. discharge at the lake outlet measured at the concrete box culvert immediately downstream of the lake outlet.

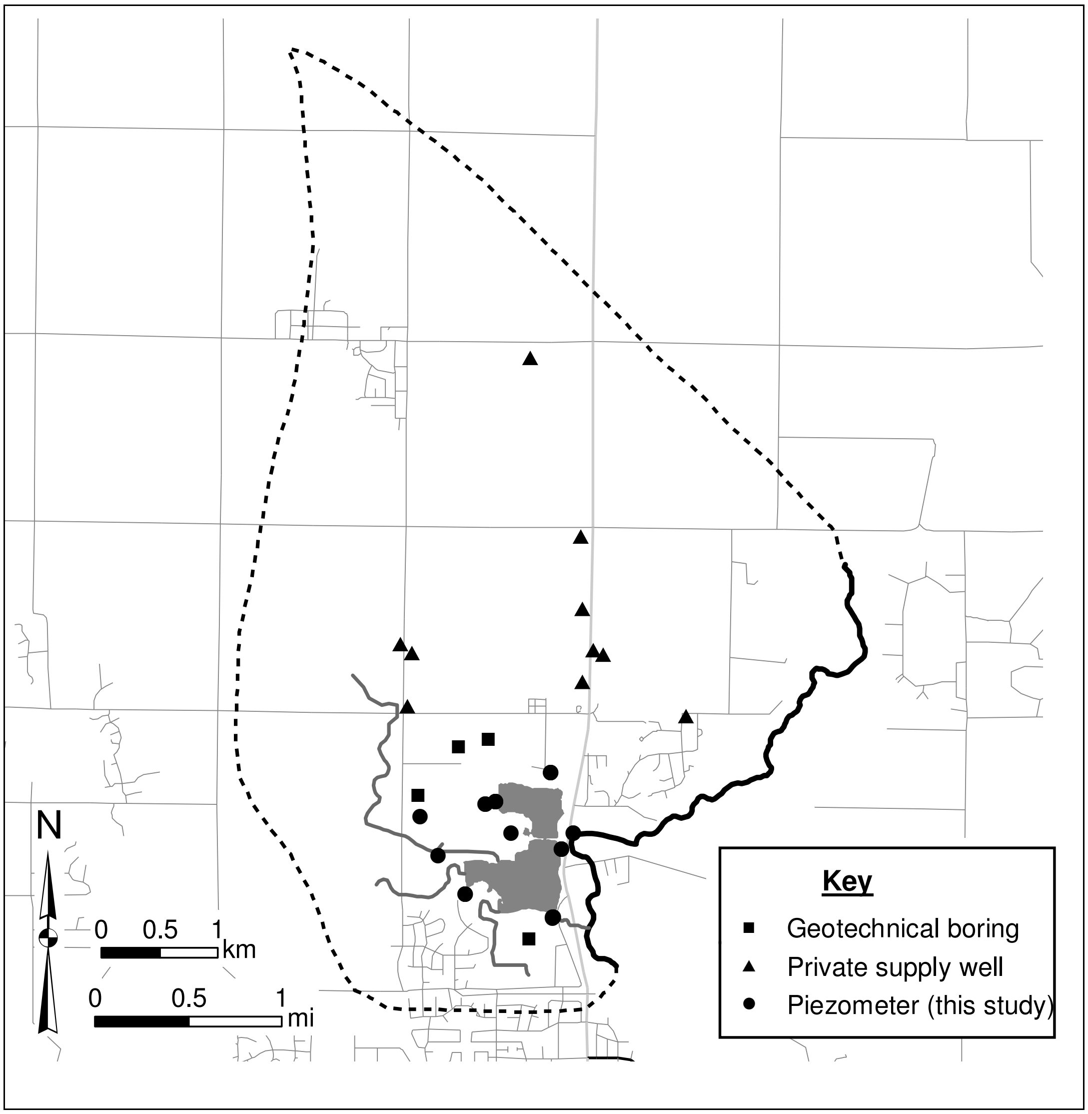


Figure 29. Location of head calibration targets for the 3-D groundwater flow model.

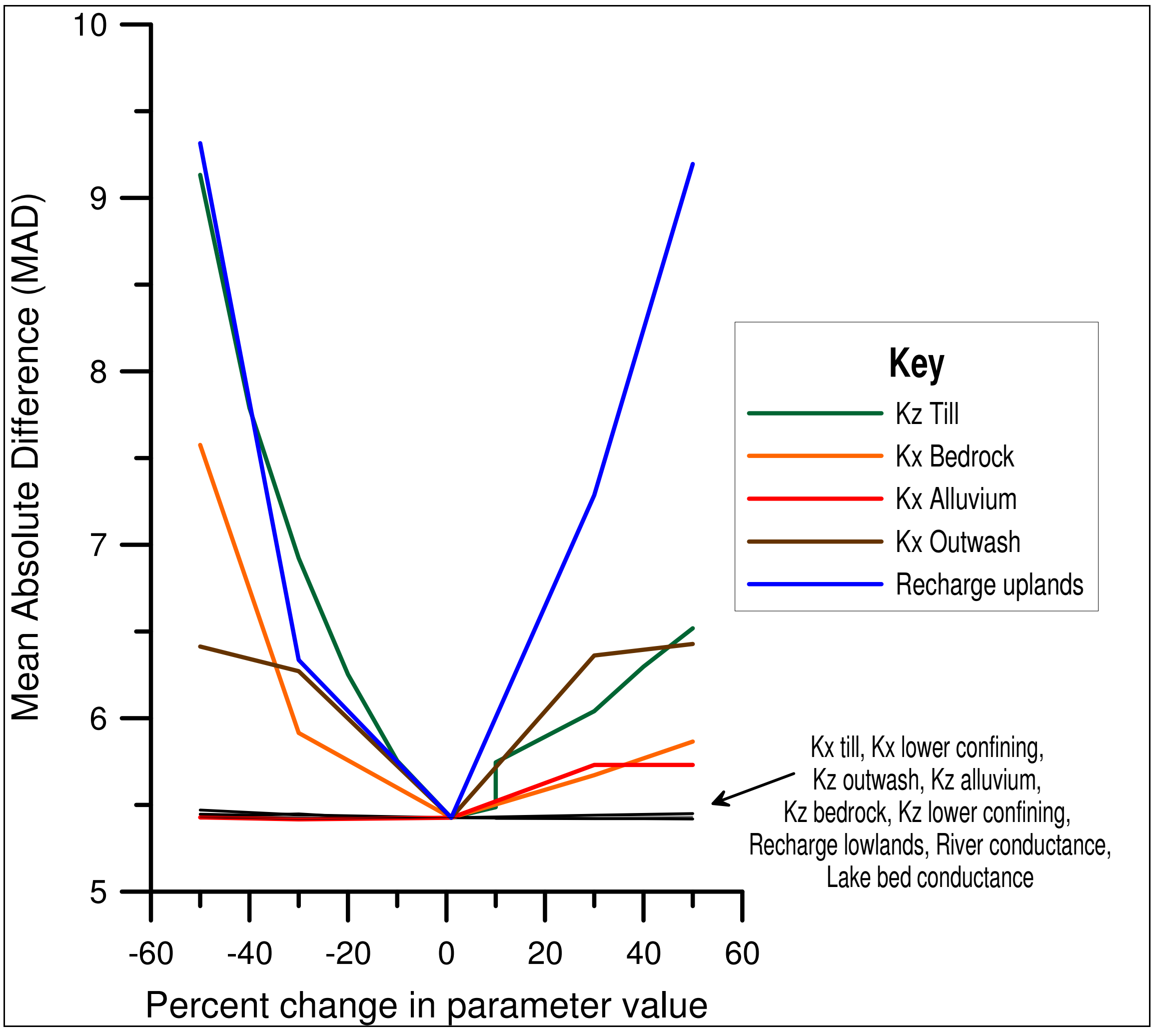


Figure 30. Model parameter sensitivities.

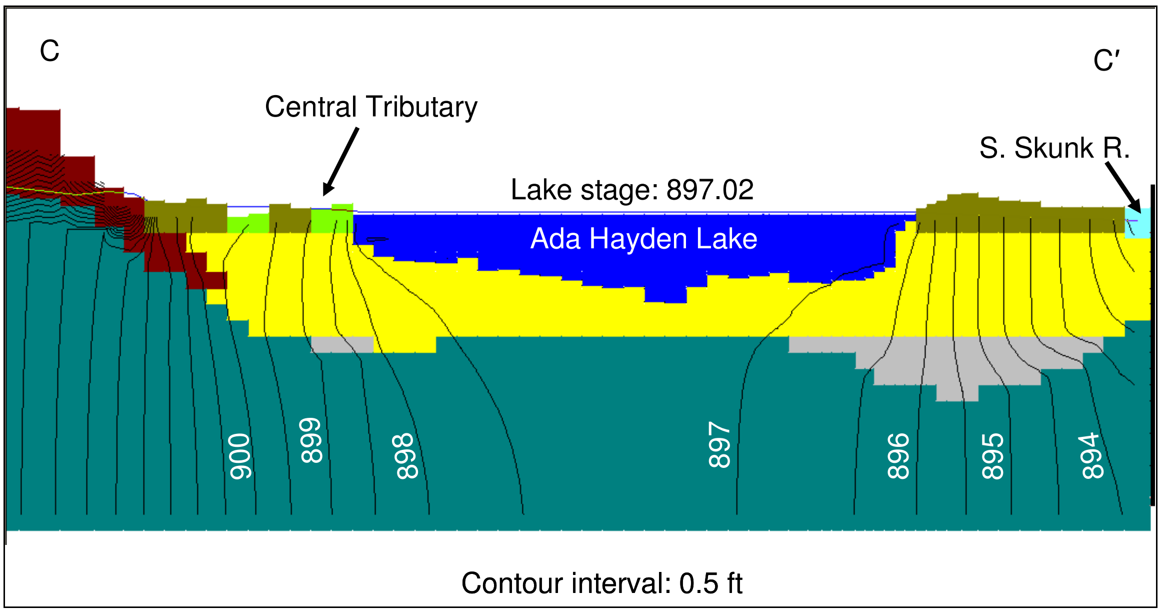


Figure 31. Cross section through row 97 of model showing that Ada Hayden Lake is a flow-through lake. Color scheme is as follows: yellow is outwash, maroon is till, tan is alluvium, gray is the lower confining unit, and blue-green is bedrock. Location of cross section is shown in Figure 32.

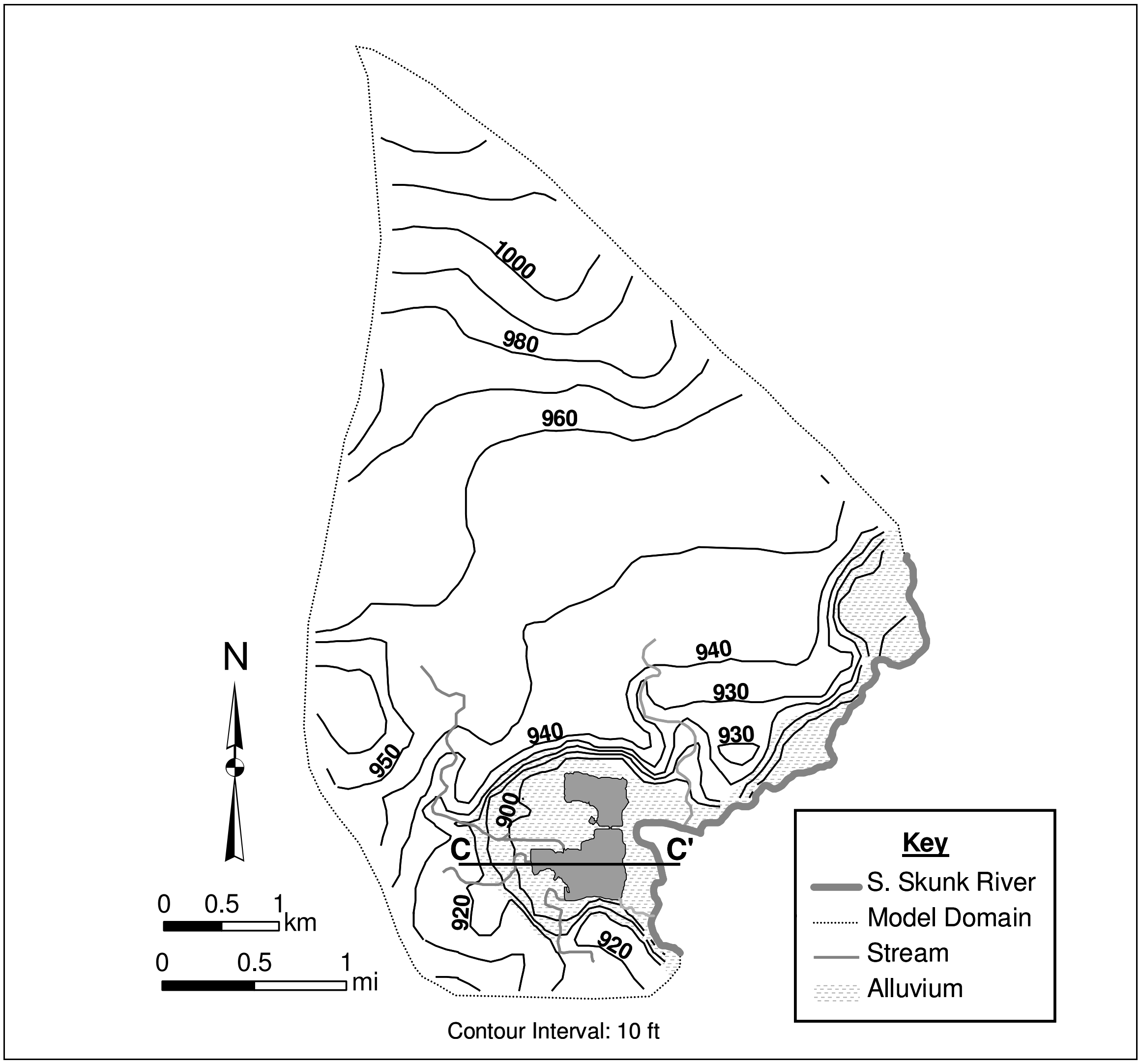


Figure 32. Map of the water-table surface based on results from the 3-D groundwater flow model. Groundwater flows south toward the lake in the middle and western part of the domain and flows into the South Skunk River on the east side. Cross section line C to C′ is shown in Figure 31.

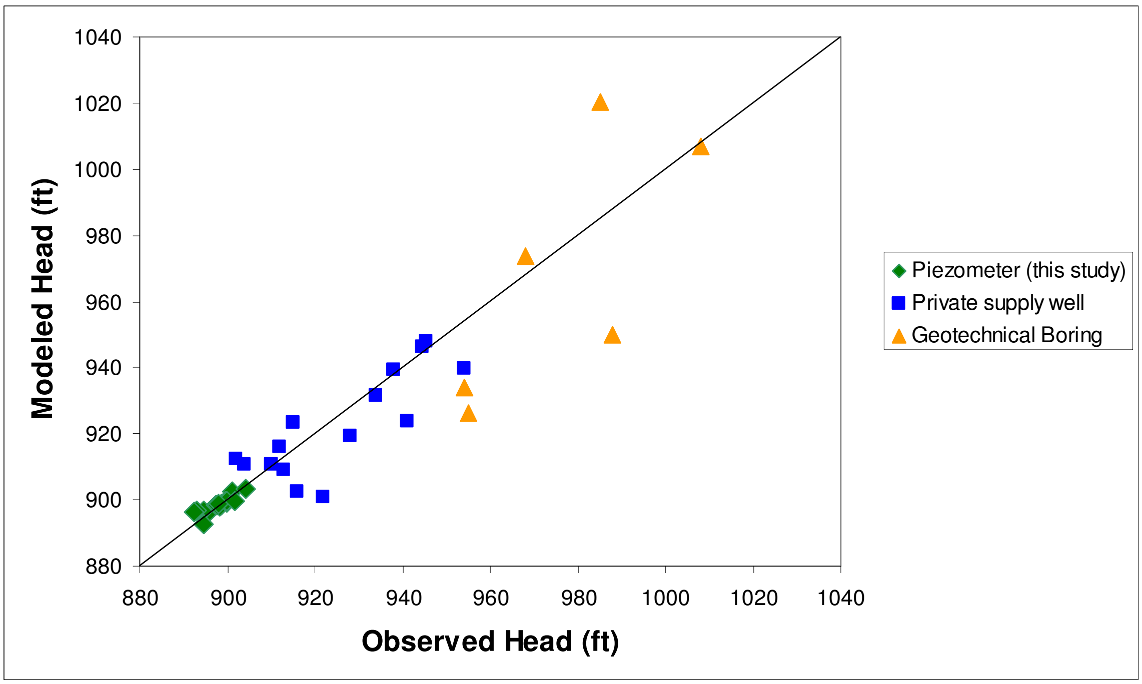


Figure 33. Calibration curve showing observed head vs. modeled head in the 3-D model. Heads immediately adjacent to the lake (897 to 905 ft) show much better relationship to measured heads. Modeled heads in the uplands (in till and bedrock), where accuracy of the data is not known, show a much greater deviation.

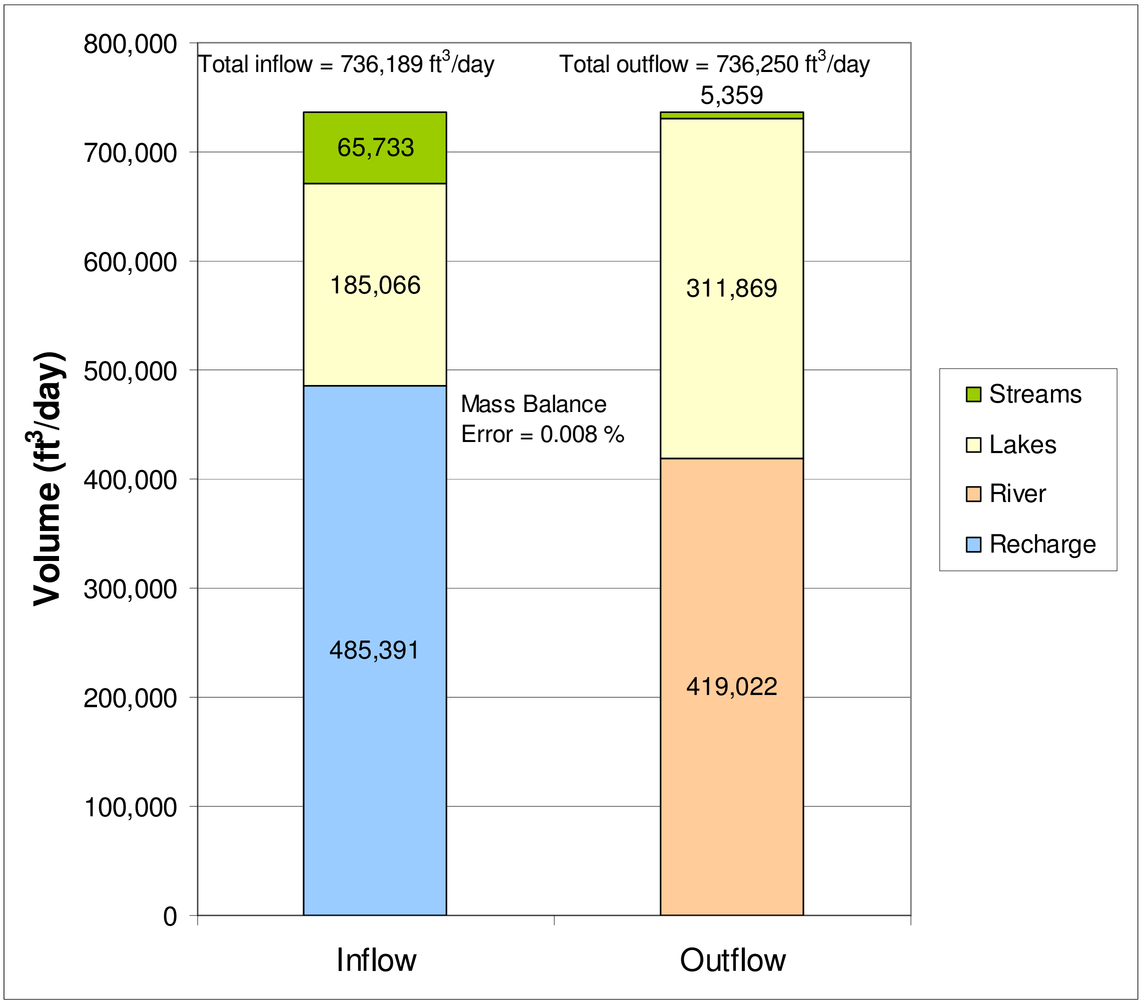


Figure 34. Model mass balance error. Note that within MODLOW, precipitation and evaporation from the lake are included in the lake value. Lake values include both Ada Hayden Lake and the nothern wetland complex. All values in ft^3/day.

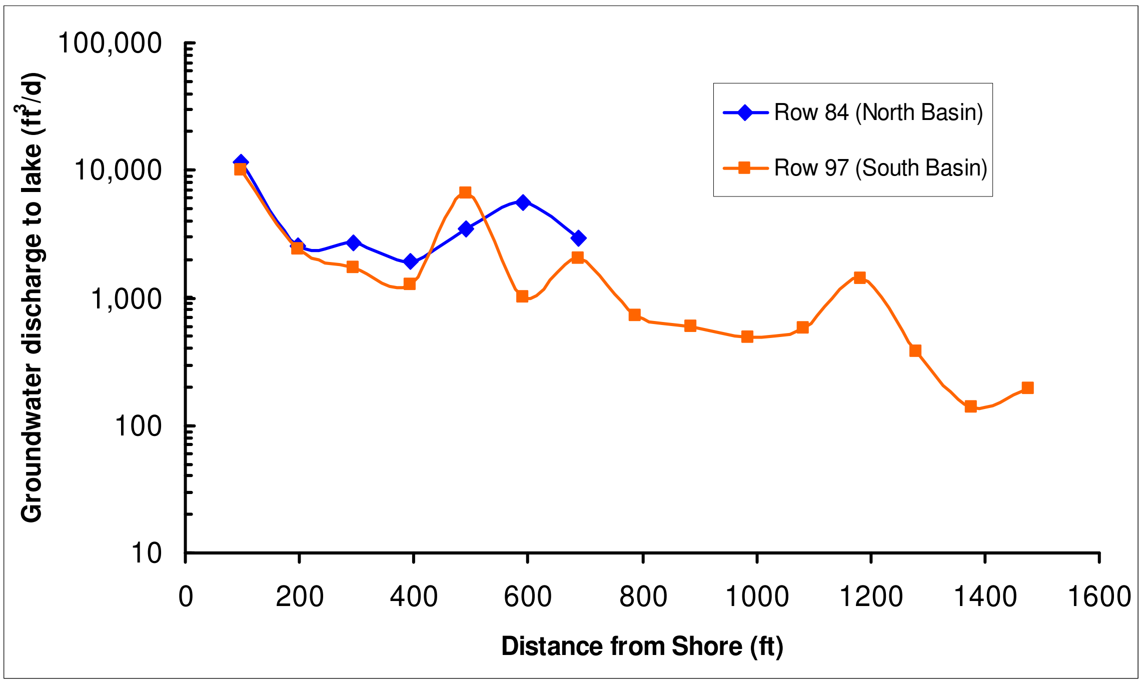


Figure 35. Groundwater discharge into lake verses distance from lake shore. Transects are west to east near the center of each basin with a distance of 0 being the western shore of the lake. The trend in Row 97 suggests adherence to the concept of a logarithmic decrease in flux with distance from the shoreline.

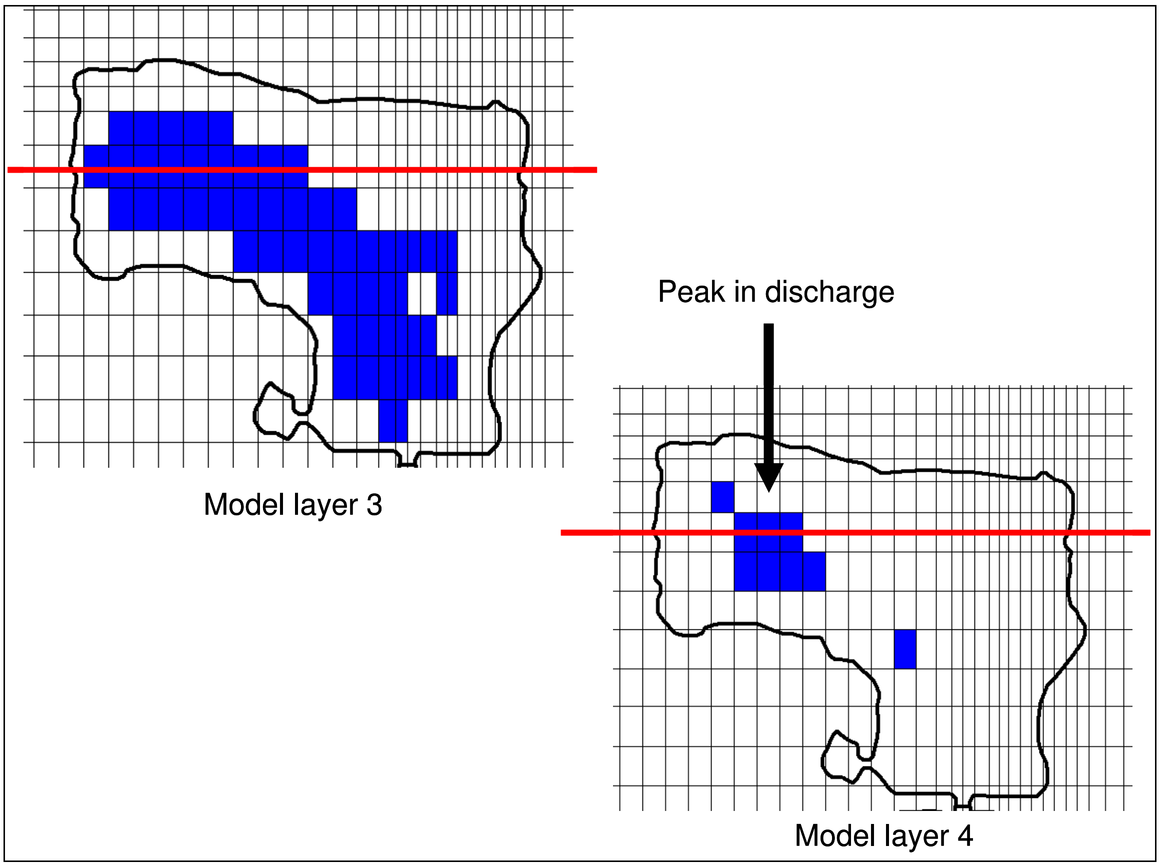


Figure 36. Configuration of lake cells for the north basin, model layers 3 and 4. Where lake model cells are not surrounded by other lake cells, a lake cell can receive groundwater from multiple directions; one explanation for the small spikes observed in groundwater discharge to the lake with distance from shore (Figure 35).

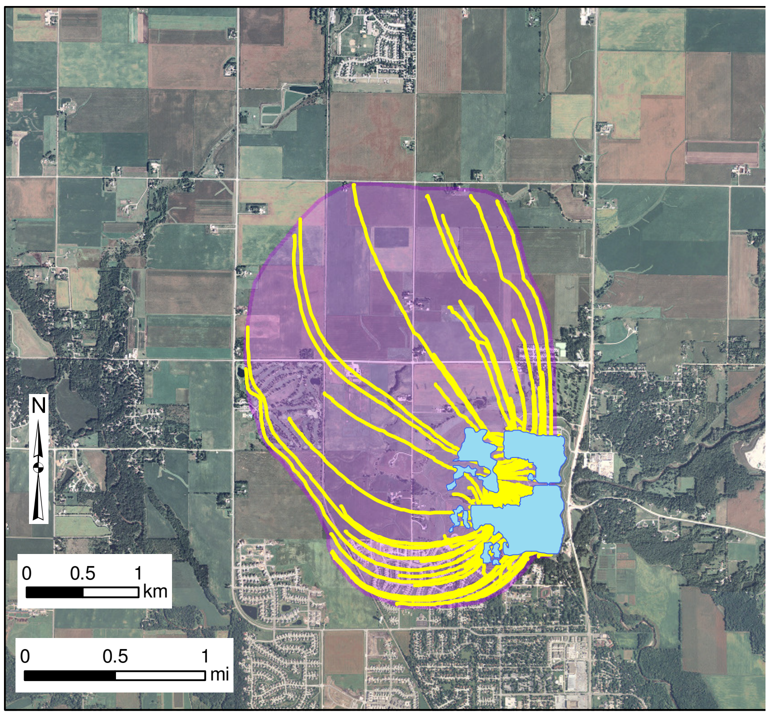


Figure 37. Particle tracks originating from the lake (layers 1-4) traced back to their point of origin (ground surface). Particle tracks define the groundwater capture zone for the lake or the ground-watershed (purple shading).

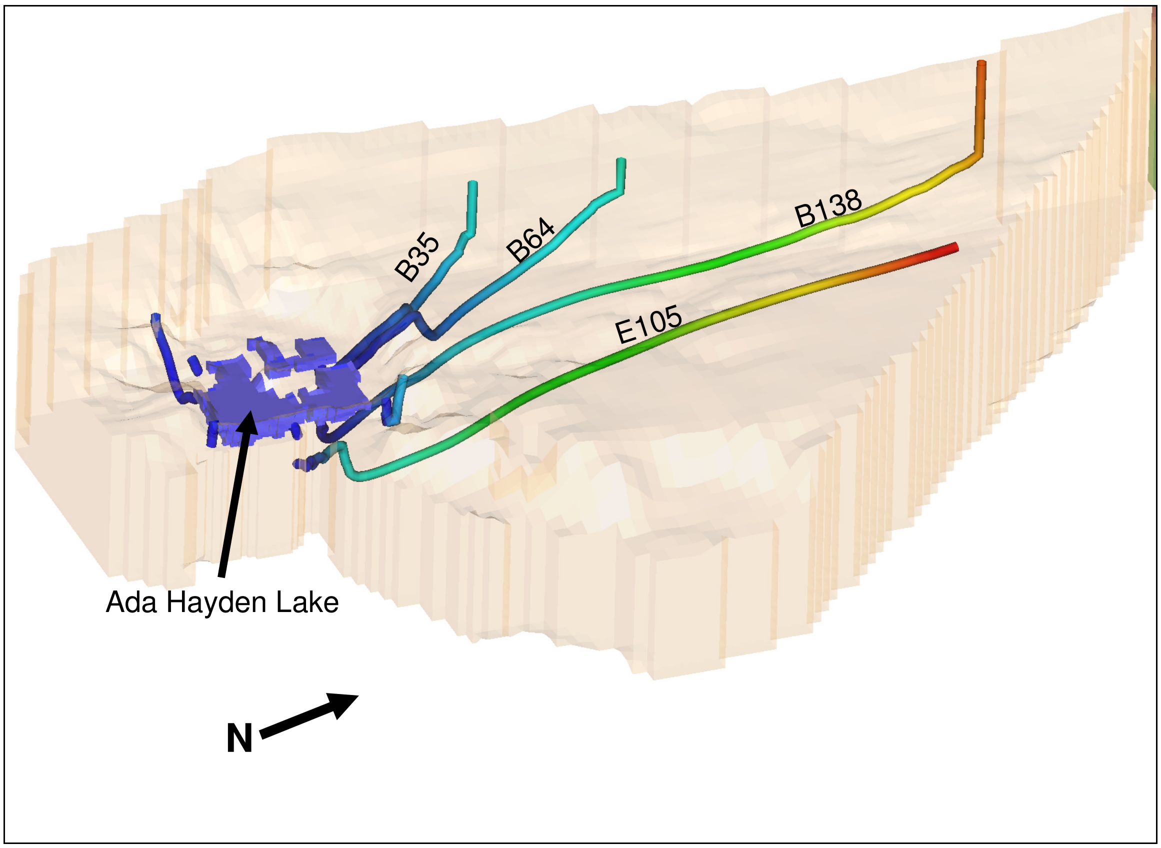


Figure 38. Particle tracks originating from piezometer screens tracked backwards for 55 years.

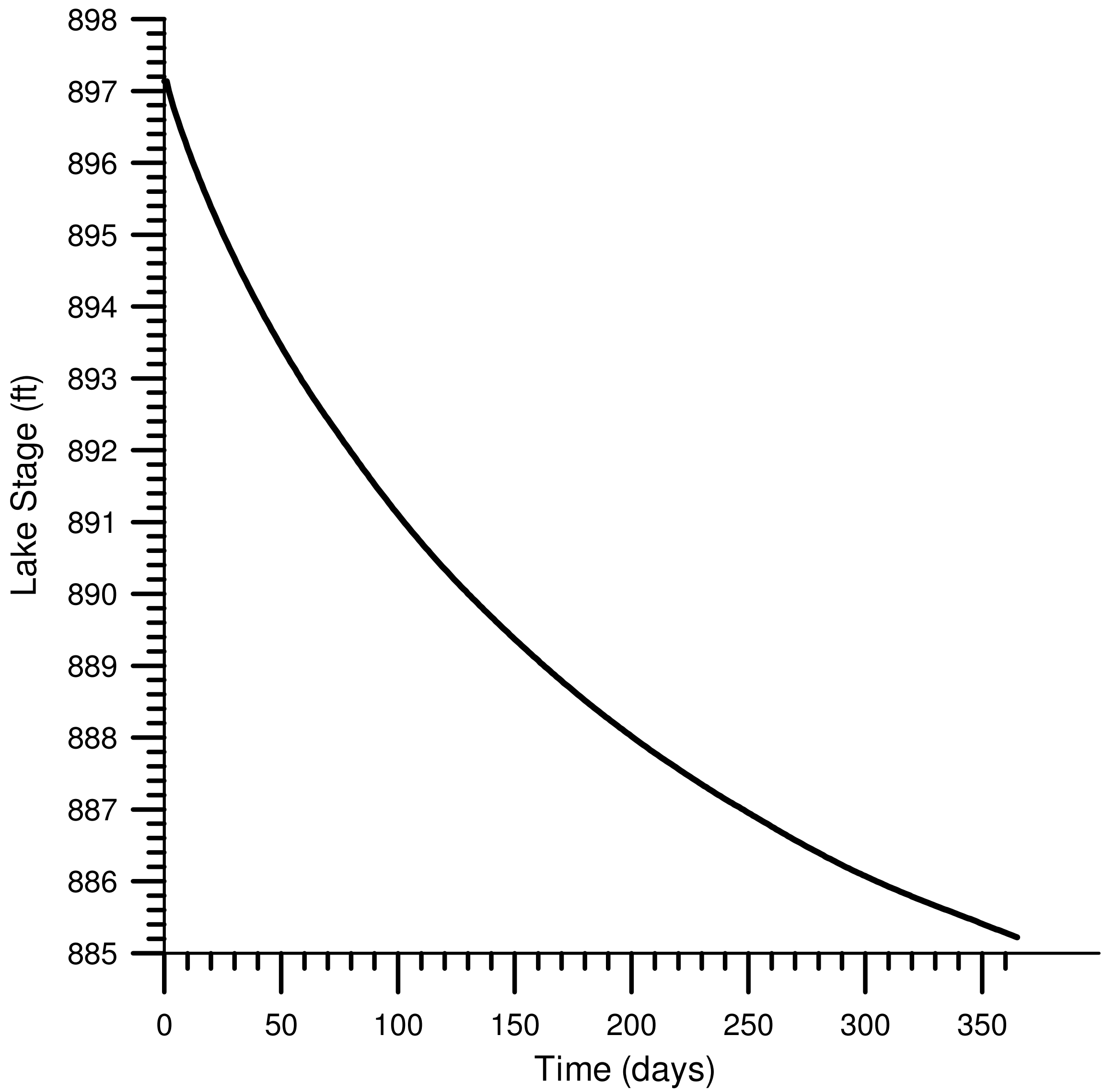
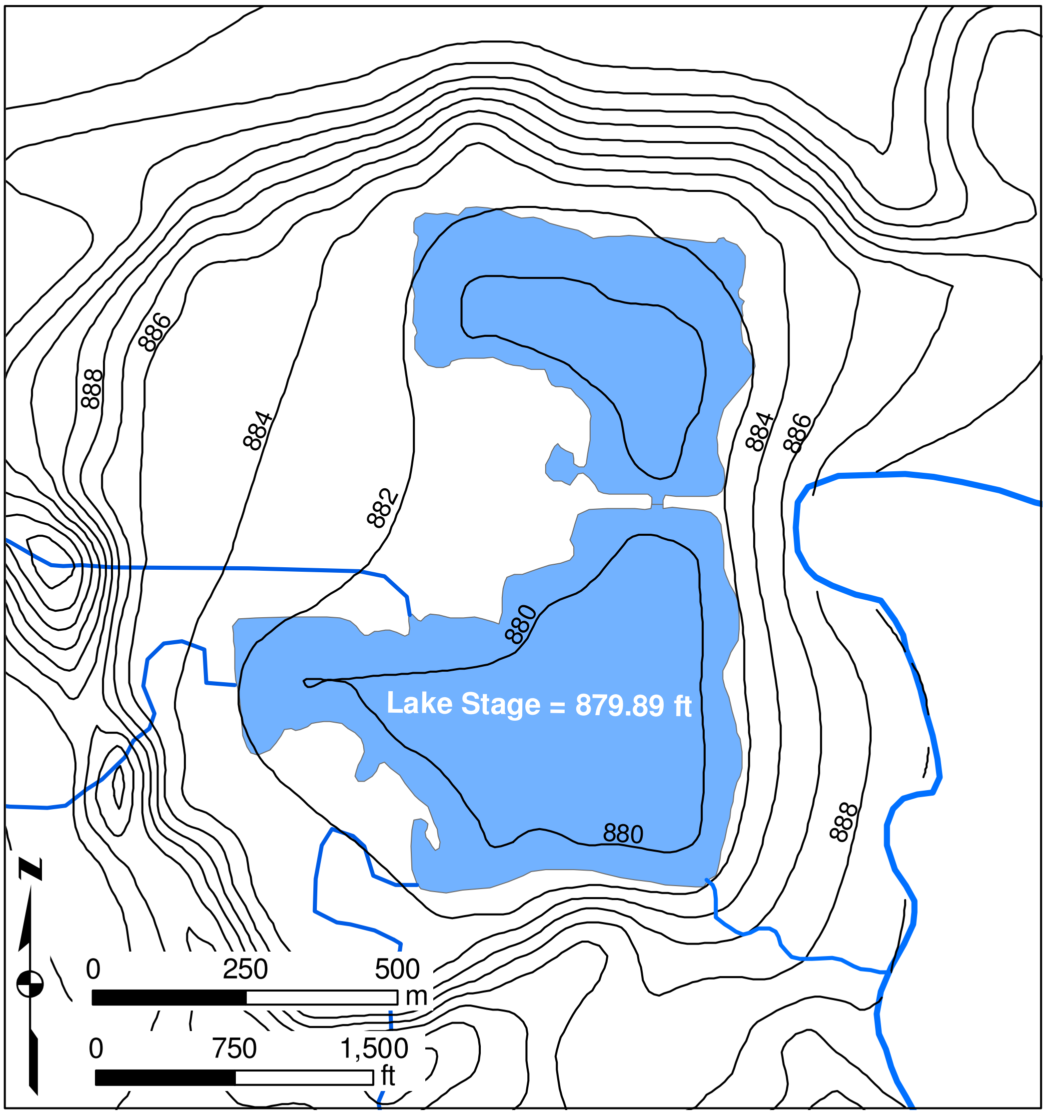


Figure 39. Simulated decline of lake stage with time as a result of pumping from the lake in the transient model.



Contour Interval: 2 ft

Figure 40. Transient model results showing map of water-table surface after one year of pumping directly from the lake surface. The hydraulic gradient reverses such that water flows from the South Skunk River into the lake.

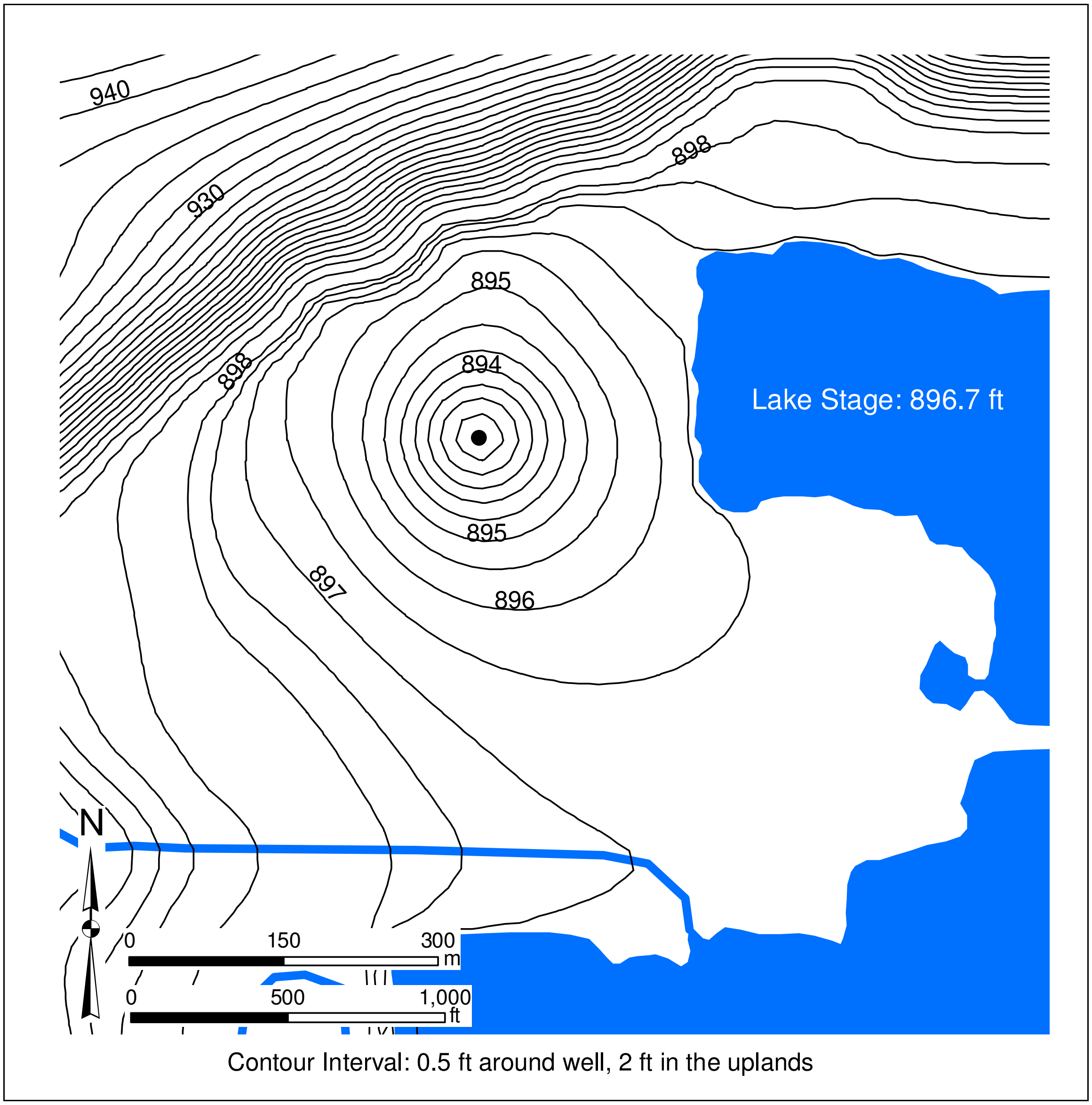


Figure 41. Transient model results showing the cone of depression developed from pumping well at 1000 gpm for one year (maximum lake stage decline of 3.75 m; 12.28 ft). Note that the hydraulic gradient is also reversed to allow groundwater to flow from the lake to the well.

Table 1. Construction data for piezometers installed in this study.

Piezometer	Depth Completed (ft)	Depth to top of screen (ft)	Depth to bottom of screen (ft)	Ground surface elevation (ft above m.s.l.)
A15	15.7	13.0	15.0	908.99
A35	34.3	31.6	33.6	909.14
A60	59.8	57.1	59.1	909.17
B13	13.0	10.3	12.3	901.84
B35	35.0	32.3	34.4	901.90
B64	64.7	62.0	64.0	902.03
B138	136.9	131.7	136.2	901.84
C15	15.0	12.3	14.3	908.73
C35	34.3	31.6	33.6	908.72
C70	69.1	66.4	68.4	908.74
D20	19.8	17.1	19.1	908.92
D35	34.9	32.2	34.2	908.91
D55	54.2	51.5	53.5	909.23
E22	21.8	19.1	21.1	907.56
E53	52.8	44.1	52.1	907.50
E105	105.2	100.3	104.3	907.48
F5	4.5	1.9	4.0	901.66
F9	8.7	6.3	8.4	901.66
G16	16.4	14.0	16.1	910.75
H10	10.3	7.9	10.0	903.94
I17[a]	17.0	15.9	16.7	903.95
J8.5[a]	8.5	7.4	8.2	900.32
J11[a]	11.0	9.9	10.7	900.20

[a] Piezometer is a Solinst model 615 drive point
Please refer to Appendix D for further piezometer construction details

Table 2. Phosphorus export coefficients (kg/ha•yr).

Land Use	Low Estimate	Best Estimate	High Estimate
Row Crop	0.5	1.0	3.0
Pasture / Grass	0.1	0.3	0.5
Residential	0.3	0.5	0.8
Rural Residential	0.05	0.1	0.25
Wetlands	0.1	0.1	0.1
Commercial	0.75	2.0	4.1
Golf Course	0.3	0.8	1.4

Data from Reckhow et al. (1980); Panuska and Kreider (2003)

Table 3. Analysis of bedrock cuttings. Samples analyzed by Brian Witzke, IGS.

Site	Depth (ft)	Formation	Description
Nest B	127 & 138	Gilmore City	Crystalline, partly fossiliferous limestone with minor smooth, gray to brown, chert.
Nest E	102	Burlington	Slightly argillaceous dolomite, no chert present
Nest D	50	Keokuk	Slightly argillaceous dolomite with a trace of quartz silt and appreciable smooth, light brown, chert.

Table 4. Results of slug testing in piezometers in this study.

Piezometer	Falling Head K (m/sec)	Rising Head K (m/sec)	Mean K (m/sec)	Lithology
A15	2×10^{-4}	2×10^{-4}	2×10^{-4}	medium sand
A35	8×10^{-9}	-	8×10^{-9}	till
A60	7×10^{-6}	9×10^{-6}	8×10^{-6}	sandy till
B13	3×10^{-4}	3×10^{-4}	3×10^{-4}	silty sand
B64	2×10^{-4}	2×10^{-4}	2×10^{-4}	coarse gravel with boulders
B138	1×10^{-7}	7×10^{-8}	9×10^{-8}	limestone
C35	2×10^{-4}	2×10^{-4}	2×10^{-4}	fine to medium sand
C70	7×10^{-4}	7×10^{-4}	7×10^{-4}	coarse sand
D20	4×10^{-7}	1×10^{-7}	3×10^{-7}	sandy silt (colluvium?)
D35	9×10^{-6}	-	9×10^{-6}	limestone
D55	1×10^{-5}	1×10^{-5}	1×10^{-5}	limestone
E22	2×10^{-4}	2×10^{-4}	2×10^{-4}	coarse sand and gravel
E53	4×10^{-5}	3×10^{-5}	4×10^{-5}	coarse gravel with boulders
E105	6×10^{-5}	8×10^{-5}	7×10^{-5}	limestone

Table 5. Environmental isotope results from groundwater and lake water samples.

Piezometer	$\delta^{18}O$	$\delta^{2}H$	% Lake Water	Enriched ^{3}H (TU)
A15	-7.618	-54.340	N/A	6.9 ± 0.9
A35	-6.344	-41.780	N/A	1.5 ± 0.3
A60	-5.928	-36.700	N/A	< 0.8 ± 0.3
B13	-4.459	-34.050	N/A	8.0 ± 0.7
B35	-5.741	-40.505	N/A	7.9 ± 0.7
B64	-6.660	-43.505	N/A	<0.8 ± 0.3
B138	-7.533	-46.365	N/A	1.3 ± 0.3
C15	-7.124	-47.655	N/A	5.5 ± 0.5
C35	-7.083	-46.955	N/A	5.8 ± 0.6
C70	-7.221	-45.790	N/A	5.6 ± 0.5
D20	-5.207	-39.825	46.4	
D35	-4.135	-31.625	74.7	
D55	-4.909	-34.830	54.3	
E22	-2.970	-27.280	100	
E53	-4.710	-35.600	59.5	
E105	-6.748	-42.205	NA	3.6 +/- 0.4
Lake near site D	-3.125	-27.070	NA	
Lake near site E	-3.220	-27.646	NA	

Table 6. Dissolved CH_4 and N_20 concentrations in groundwater.

Piezometer	CH_4 (µmol/L)	N_2O (µmol/L)
A15	0.023	0.126
A35	3.66	0.105
A60	151.3	0.035
B13	0.793	0.006
B35	2.04	0.006
B64	195.7	0.007
B138	1.98	0.045
C15	0.200	2.15
C35	0.923	0.082
C70	7.22	0.013
D20	108.1	0.035
D35	27.66	0.012
D55	7.74	0.021
E22	21.77	0.006
E53	2.94	0.008
E105	3.92	0.010

Table 7. Mean of chemical parameters determined from monthly sampling of groundwater.

Piezo.	NH_3-N (mg/L)	NO_3-N (mg/L)	Total P (µg/L)	Soluble Reactive P (µg/L)	Total C (mg/L)	Organic C (mg/L)	pH	Alkalinity (mg/L) as $CaCo_3$	Temp (ºC)	Dissolved O_2 (mg/L)	Elect. Cond. (µS)	Spec. Cond. (µS)
A 15	0.00	6.78	59.7	10.3	72.9	3.72	7.46	302.4	11.8	6.1	223.8	281.1
A 35	0.28	0.42	50.2	16.2	105.7	4.38	7.59	440.9	11.5	<2.0	230.0	309.3
A 60	1.76	0.00	337.6	305.9	106.9	3.12	7.73	454.4	11.3	<2.0	231.1	300.1
B 13	0.17	0.00	42.2	33.5	64.5	2.68	7.56	255.6	12.6	<2.0	212.4	270.8
B 35	1.43	0.00	269.1	258.6	83.1	3.07	7.62	336.4	11.6	<2.0	212.1	286.4
B 64	1.89	0.00	220.2	209.3	96.1	2.45	7.78	403.0	11.0	<2.0	207.4	283.8
B 138	0.53	0.06	13.7	5.7	98.2	1.39	7.53	402.2	11.9	<2.0	242.6	324.0
C 15	0.00	0.52	181.3	15.1	154.9	2.07	6.87	474.9	12.2	4.4	356.6	465.1
C 35	0.00	2.02	5.9	1.6	70.0	1.06	7.65	240.1	11.3	<2.0	194.3	255.4
C 70	0.37	0.06	50.1	44.9	63.8	1.51	7.60	268.4	10.9	<2.0	231.3	288.0
D 20	0.88	0.93	365.8	465.5	134.1	5.67	7.09	529.8	12.0	4.2	282.1	361.2
D 35	0.63	0.01	247.3	133.0	82.0	3.80	7.33	673.7	11.6	5.7	210.4	281.6
D 55	1.15	0.12	54.8	45.0	62.6	2.32	7.67	270.4	11.5	<2.0	184.9	249.5
E 22	0.21	0.00	100.9	81.5	54.7	1.84	7.64	229.6	13.3	<2.0	187.3	237.8
E 53	0.55	0.12	36.0	16.8	66.7	1.68	7.69	292.7	12.5	<2.0	200.1	258.9
E 105	0.67	0.02	56.0	42.9	68.4	1.93	7.82	288.6	12.0	<2.0	192.1	251.2
F5	0.00	0.00	144.0	113.0	106.7	4.56	7.10	405.8	-	<2.0	-	-
F9	1.30	0.00	234.5	310.2	77.7	6.09	6.82	426.0	-	<2.0	-	-
G16	0.00	2.17	56.6	11.1	171.0	0.94	7.65	296.5	12.5	3.9	188.2	247.3
H10	0.00	0.58	17.7	14.4	219.3	1.94	7.23	353.5	12.4	<2.0	233.9	309.3
I17	1.15	0.00	96.8	0.0	59.1	3.94	8.27	723.0	-	<2.0	-	-
J8.5	0.00	3.96	33.78	11.5	79.2	1.29	7.52	354.0	-	<2.0	-	-
J11	0.00	0.00	35.23	22.1	75.9	1.24	7.76	650.0	-	6.5	-	-

Notes: If 0.00 then the value is below the minimum detection limit (MDL) or practical quantitation limit (PQL)

Table 8. Major and trace elements determined by ICP-OES. SiO_2 determined colorimetrically.

Piezo.	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	S (ppm)	Zn (ppm)	B (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)	Al (ppm)	Na (ppm)	Si as SiO_2 (mg/L)
A 15	0.03	0.68	108.04	31.91	13.61	0.18	0.02	0.01	0.04	0.01	0.02	4.17	23.59
A 35	0.01	5.13	92.27	31.34	3.39	0.11	0.97	0.28	0.06	0.01	0.04	46.18	24.36
A 60	0.26	6.26	91.43	34.56	0.66	0.14	0.77	0.07	3.63	0.01	0.02	42.63	32.37
B 13	0.01	2.35	96.77	23.61	17.90	0.13	0.06	0.63	2.70	0.01	0.01	7.59	21.57
B 35	0.35	3.73	104.05	37.45	17.56	0.34	0.12	0.07	4.76	0.01	0.06	16.66	39.34
B 64	0.18	3.89	86.99	32.06	0.67	0.37	0.19	0.06	5.21	0.01	0.03	24.65	34.13
B 138	0.03	7.25	91.55	47.66	31.37	0.04	0.36	0.06	1.59	0.01	0.02	34.21	11.42
C 15	0.03	0.74	166.67	43.91	68.71	0.01	0.04	0.67	0.47	0.02	0.02	31.69	31.48
C 35	0.01	0.37	104.94	32.55	32.77	0.27	0.02	0.37	0.06	0.01	0.01	3.91	19.89
C 70	0.03	1.20	95.45	29.71	19.66	0.05	0.01	0.28	1.09	0.01	0.01	9.23	33.29
D 20	0.38	1.46	184.85	35.36	2.28	0.16	0.50	4.05	19.61	0.01	0.01	12.34	109.18
D 35	0.19	2.11	94.69	24.68	6.84	0.08	0.14	0.39	7.44	0.01	0.01	11.91	29.57
D 55	0.05	2.78	67.21	26.86	12.20	0.01	0.11	0.13	1.40	0.01	0.01	17.32	24.48
E 22	0.07	1.67	65.31	21.15	6.39	0.12	0.05	0.40	2.76	0.01	0.05	15.02	33.08
E 53	0.02	2.70	83.97	30.26	19.61	0.19	0.07	0.16	2.39	0.01	0.01	13.73	24.69
E 105	0.04	3.44	88.81	33.96	13.48	0.06	0.17	0.10	1.33	0.01	0.01	21.03	17.52

Note: All samples except Si collected on August 30, 2006
Si samples collected on October 25, 2006

Table 9. Major anions and other chemical parameters sampled from groundwater.

Piezometer	Temp °C	Spec. Cond. (uS)	Dissolved O_2 (mg/L)	pH	F (ppm)	Cl (ppm)	Br (ppm)	NO_3 (ppm)	PO_4 (ppm)	SO_4 (ppm)
A 15	13.3	291.1	5.6	7.53	0.01	11.33	< 0.01	38.71	< 0.02	41.33
A 35	11.9	285.5	0.3	7.50	0.23	4.73	< 0.01	< 0.01	< 0.02	10.82
A 60	11.6	292.2	<0.2	7.76	0.18	1.79	< 0.01	< 0.01	< 0.02	1.45
B 13	15.1	267.6	<0.2	7.46	0.65	39.12	< 0.01	< 0.01	< 0.02	55.51
B 35	11.7	278.6	<0.2	7.58	0.04	17.32	< 0.01	< 0.01	< 0.02	55.17
B 64	10.9	257.1	<0.2	7.74	0.17	2.06	< 0.01	< 0.01	< 0.02	4.05
B 138	12.4	308.8	<0.2	7.54	1.77	5.10	< 0.01	< 0.01	< 0.02	115.75
C 15	12.8	247.9	3.7	7.23	< 0.01	35.69	0.17	17.15	< 0.02	271.00
C 35	11.4	247.4	<0.2	7.65	< 0.01	30.01	< 0.01	22.65	< 0.02	118.02
C 70	11.0	177.4	<0.2	7.58	0.03	56.10	< 0.01	< 0.01	< 0.02	69.27
D 20	11.9	286.5	<0.2	6.97	0.09	34.66	< 0.01	< 0.01	< 0.02	2.10
D 35	11.5	273.3	<0.2	7.25	0.15	30.07	< 0.01	< 0.01	< 0.02	23.81
D 55	11.5	226.1	<0.2	7.69	0.13	27.14	< 0.01	< 0.01	< 0.02	41.82
E 22	14.2	233.1	<0.2	7.62	0.14	27.23	< 0.01	< 0.01	< 0.02	20.06
E 53	12.7	244.1	<0.2	7.66	0.22	16.75	< 0.01	< 0.01	< 0.02	69.94
E 105	12.1	261.5	<0.2	7.75	0.57	18.00	< 0.01	< 0.01	< 0.02	46.45

Note: Samples collected on August 30, 2006

Table 10. Saturation indices for select minerals determined by PHREEQC (v.2). Negative values indicate that groundwater is saturated with respect to a mineral. Positive values indicate that groundwater is undersaturated with respect to a mineral. Values near zero are at equilibrium.

Piezometer	CO_2	Calcite	Dolomite	Siderite	Hydroxyapatite	FeS	Mackinawite
A 15	-2.06	0.45	0.54	-10.75	-1.09	-153.55	-152.82
A 35	-1.86	0.50	0.68	-10.06	-3.11	-151.66	-150.93
A 60	-2.12	0.75	1.22	1.36	2.17	-0.05	0.68
B 13	-2.08	0.27	0.14	-0.15	-2.75	1.90	2.64
B 35	-2.04	0.53	0.76	0.92	2.02	2.45	3.18
B 64	-2.16	0.65	1.00	1.46	1.50	0.43	1.16
B 138	-1.98	0.44	0.73	-0.63	-1.74	1.53	2.27
C 15	-1.66	0.36	0.32	-9.28	-2.10	-150.58	-149.84
C 35	-2.31	0.39	0.42	-0.95	-2.25	-3.92	-1.38
C 70	-2.20	0.33	0.29	-0.17	-1.26	1.76	2.49
D 20	-1.26	0.31	0.06	1.36	0.07	2.08	2.82
D 35	-1.75	0.14	-0.16	0.85	-0.32	2.34	3.07
D 55	-2.33	0.28	0.31	0.70	-0.68	1.57	2.30
E 22	-2.27	0.24	0.19	0.98	-0.26	1.68	2.41
E 53	-2.22	0.43	0.60	0.96	-1.57	1.93	2.66
E 105	-2.23	0.62	0.97	0.85	-0.28	0.88	1.61

Table 11. Parameter values used in the model.

Parameter	Model Units	Metric Equiv.
Till K_x		
Initial Model	3.0×10^{-2} ft/d	9.1×10^{-3} m/d
Calibrated Model	2.8×10^{-2} ft/d	8.5×10^{-3} m/d
Till K_z		
Initial Model	3.0×10^{-3} ft/d	9.1×10^{-4} m/d
Calibrated Model	2.8×10^{-3} ft/d	8.5×10^{-4} m/d
Alluvium K_x		
Initial Model	12 ft/d	3.7 m/d
Calibrated Model	17 ft/d	5.2 m/d
Alluvium K_z		
Initial Model	2.5 ft/d	0.76 m/d
Calibrated Model	3.0 ft/d	0.9 m/d
Outwash K_x		
Initial Model	500 ft/d	152 m/d
Calibrated Model	177.2 ft/d	54 m/d
Outwash K_z		
Initial Model	5.0 ft/d	1.5 m/d
Calibrated Model	5.0 ft/d	1.5 m/d
Bedrock K_x		
Initial Model	15.5 ft/d	4.72 m/d
Calibrated Model	20.4 ft/d	6.2 m/d
Bedrock K_z		
Initial Model	1.5 ft/d	0.46 m/d
Calibrated Model	2.10 ft/d	0.6 m/d
Lower Till/Loess K_x		
Initial Model	2.0×10^{-4} ft/d	6.1×10^{-5} m/d
Calibrated Model	2.0×10^{-4} ft/d	6.1×10^{-5} m/d
Lower Till/Loess K_z		
Initial Model	2.0×10^{-4} ft/d	6.1×10^{-5} m/d
Calibrated Model	2.0×10^{-4} ft/d	6.1×10^{-5} m/d
Recharge, Uplands		
Initial Model	7.0 in/yr	17.5 cm/yr
Calibrated Model	7.3 in/yr	18.6 cm/yr
Recharge, Lowlands		
Initial Model	7.5 in/yr	19.0 cm/yr
Calibrated Model	7.8 in/yr	20.1 cm/yr
Skunk River width	50 ft	15.2 m
Skunk River bed thickness	5 ft	1.5 m
Skunk River bed K	100 ft/d	30.5 m/d
Tributary width	3 ft	0.9 m
Tributary bed thickness	3 ft	0.9 m
Tributary bed K	10 ft/d	3.0 m/d
Lakebed thickness	2 ft	0.3 m
Lakebed K	1.5 ft/d	0.46 m/d
Precipitation on lake	37 in/yr	94.0 cm/yr
Evaporation from lake	39 in/yr	99.1 cm/yr

Table 12. Water balance for Ada Hayden Lake determined by the groundwater model.

Input	Discharge (ft^3/d)	Output	Discharge (ft^3/d)
Groundwater	275,470	Groundwater	116,150
Precipitation	46,567	Evaporation	49,086
Streamflow	2752	Streamflow	159,370
Total	324,789	**Total**	324,606

Table 13. Comparison of P loads and predicted P concentration from the groundwater model and studies by BRAA (2000) and Antosch (1982). In-lake concentrations from Downing (2006).

Authors	Flushing rate (1/yr)	Total P load to Lake (kg/yr)	Lake P concentration (μg/L)
This Study	0.69	617[a]	80-104[b]
BRAA (2000)	0.45	354	62-80
Antosch (1982)	0.47	489	56.8
Downing (2006)	N/A	N/A	17.94-120.86[c]

[a] value using mean SRP for groundwater and 50% loss of P in wetlands
[b] range using mean SRP for groundwater and both no loss of P in wetlands and 50% loss of P in wetlands
[c] range of measured, mixed lake, P concentrations 2001-2005

APPENDIX A

CORE DESCRIPTION

Site B

Depth (ft)	**Description**
0.0 to 0.6	Silt loam (2.5Y 2.5/1), non-calcareous, lack of structure, many fine roots, possible fill material
0.6 to 3.2	Silt loam (10YR 2/1), calcareous, granular to subangular blocky structure
3.2 to 4.1	Silt to clay loam (10YR 3/1), calcareous, subangular block structure, more cohesive near bottom
4.5 to 4.6	Silt to clay loam (2.5 Y 5/3), mixed with 7.5 YR 4/6 jumbled mess, non-calcareous
4.6 to 5.25	Silt (gley 1 6/10 Y), some 10 YR 3/6 mottles, non-calcareous, some 10 YR 3/2 dark areas
5.25 to 6.1	Silty clay (gley 1 6/10Y), mottles 10 YR 3/2, lose streaky stuff, non-calcareous, 2.5 YR 4/1 reduction spot at 5.8 ft 6.1 to 7.5 Silty clay (gley 2 6/10G), non-calcareous, 6.1 to 6.3 ft 7.5 YR 4/1 large reduction spot associated with a pebble (bog iron), lose iron mottles
7.5 to 7.55	Silt loam (as above), non-calcareous
7.55 to 8.52	Silty sand (2.5Y 5/1) with carbon streaks, intact small wood chunks, non-calcareous
8.52 to 9.2	Coarser sand, (2.5Y 5/1) with flecks of carbon, non-calcareous
9.5 to 11.5	Gravel, 2.5 Y 5/1, non-calcareous, highly oxidized with Fe-oxidizing bacteria; acid addition release H_2S gas, core oxidized to 1 cm outside
11.5 to 12.3	Coarse gravel, (2.5Y 5/1), non-calcareous, more oxidized near bottom
14.5 to 15.5	Coarse gravel, sandier on top (2.5Y 4/1 to 5/1), slightly calcareous, H_2S emitted
15.5 to 16.9	Cohesive silty sand (2.5Y 4/1), gravel coating outside of core, calcareous, H_2S emitted, hot oxidation spot at 16.9 ft
19.5 to 21.1	Medium sand (2.5Y 4/1), calcareous, Fe/Mn splotches on outside
21.1 to 21.5	Find sand with silt (2.5 Y 5/1), calcareous, core is dark gray with thin Fe-oxidized rim
24.5 to 27.1	Fine sand (2.5Y 5/1), calcareous, no wood, heavily oxidized (3 months), some Fe splotches on outside
29.5 to 31.8	Fine sand (salt and pepper appearance, 2.5Y 5/1), calcareous, no wood, massive appearance, small Fe splotches on core
34.5 to 35.1	Fine to medium sand (2.5Y 5/1 matrix with swirls of darker 2.5 Y 3/1 silt or carbon), only slightly calcareous (old soil A horizon?
35.1 to 36.6	Fine to medium sand (2.5Y 5/1 matrix), very uniform, more calcareous than above, Fe splotches throughout core
39.5 to 41.2	Fine to medium sand (2.5Y 5/1 matrix), calcareous, some high chroma Fe splotches on outside with darker spots
44.5 to 45.0	Fine to medium sand, (2.5Y 4/1), some pebbles, calcareous
45.0 to 45.6	Gravel seam
45.6 to 46.5	Fine to medium sand, (2.5Y 4/1), some pebbles, calcareous
49.5 to 49.8	Fine to medium sand, (2.5Y 4/1 to 5/1), some pebbles, calcareous, dark spots (Mn oxidation?)
49.8 to 51.1	Coarse gravel mixture, various colors, now oxidized, not much Fe on outside
54.4 to 54.9	Coarse gravel mixture
54.9 to 55.2	Medium to coarse sand, (2.5Y 5/1), calcareous
55.2 to 56.1	Very, very coarse gravel, cobbles (0.15 ft diameter)
59.5 to 59.7	Medium to coarse sand (2.5Y 5/1), very calcareous

59.7 to 61.0	Coarse gravel mixture, various colors
64.0 to 64.5	Fine sand (2.5 Y 5/1), calcareous, mixed with big granite pebbles, acid addition emits H_2S plus other petroleum-like odor, no Fe splotches in this section
67.0 to 67.5	Coarse sand and gravel
67.5 to 69.0	Very coarse gravel, Fe-splotches on outside
67.9 to 68.3	Diamicton, possible Dows Formation till (2.5Y 4/1), calcareous

Bag samples

72 to 81	Coarse gravel, calcareous (bit sample)
84 to 103	Gravel with some sand, calcareous, good wood at 84 ft (bit sample)
105 to 117	Till (2.5 Y 4/1), slightly calcareous (bit sample), C-14 date > 44,770 RCYBP.
117	Limestone bedrock (cuttings), Mississippian, Gilmore City Formation.

Site E

Depth (ft)	Description
0.90 to 2.70	Loamy fill (2.5Y 2.5/1), organic, some roots, many pebbles, calcareous
4.50 to 7.30	Loamy fill (2.5Y 3/1) old soil, upper 1 ft calcareous but not much below
7.30 to 8.50	Silty loam (2.5Y 3/1), not as organic, cohesive, structureless
9.50 to 14.00	Pea gravel road material
14.00 to 14.50	Sand and fine gravel (10YR 4/3), calcareous, roots, oxidized
14.50 to 15.80	Sand and fine gravel (2.5Y 5/1), calcareous, H_2S emitted with acid, Fe splotches begin in finer grained sections
19.50 to 19.60	Silty gravel (2.5Y 4/1), not calcareous, perhaps floodplain soil
19.60 to 20.40	Coarse sand and fine gravel (2.5Y 4/1), not really calcareous, Fe splotches
24.50 to 25.40	Coarse sand and fine gravel (2.5Y 5/1), calcareous, Fe splotches and dark spots
25.40 to 26.40	Very coarse sand and gravel (2.5Y 5/1), calcareous, large 0.07 ft pebbles/cobbles
29.5 to 31.3	Coarse sand and fine gravel (2.5Y 5/1), calcareous, few large 0.08 ft cobbles, not much Fe on outside, dark Mn? Spots
34.5 to 35.9	Coarse sand with some fine gravel (2.5Y 5/1), calcareous, devoid of Fe splotches
39.5 to 40.45	Coarse sand and fine gravel (2.5Y 5/1), calcareous, lots of leopard dark Fe splotches
44.5 to 46.5	Medium sand (2.5Y 4/1), upper part slightly calcareous, bottom part calcareous, some bentonite contamination on sample
Bag samples	
50	Coarse gravel, cuttings from boulders
55	Coarse gravel, bentonite intrusions
57	Coarse gravel
62 to 65	Coarser gravel than above, wetter
69	Till (2.5 4/1), very calcareous, dense, looks like Dows Formation (bit sample)
75 to 78	Silty till (2.5 Y 4/1), maybe mixed with loess, slightly calcareous, some pebbles (bit sample)
81 to 88	Paleosol? (2.5Y 5/2), no pebbles, very sticky, non-calcareous, note color change (bit sample)
93	Paleosol? (2.5Y 5/1) or limestone residuum material, slightly darker color, calcareous (bit sample)

APPENDIX B

PARTICLE SIZE ANALYSES

Table B 1. Particle size percentage, USDA scale.

Sample ID	Depth (ft)	% Sand	% Silt	% Clay	USDA Soil Texture
B1	5.6-5.8	22.57	49.39	28.04	clay loam
B2	8.6-8.8	87.90	12.10	0.00	sand
B3	11.9-12.1	93.39	3.30	0.00	sand
B11	21.1-21.5	88.37	5.23	6.39	sand
B4	31.6-31.8	96.74	3.25	0.00	sand
B5	46.2-46.4	97.98	2.02	0.00	sand
B6	55.6-56.1	94.75	2.62	2.60	sand
B7	60.2-60.5	97.55	2.45	0.00	sand
B8	64.5-64.8	93.27	4.85	1.88	sand
B9	67.9-68.3	70.17	19.42	10.41	sandy loam
B10	109	56.29	22.13	21.58	sandy clay loam
E1	15.2-15.4	95.12	4.88	0.00	sand
E2	20.0-20.2	86.66	13.33	0.00	sand
E3	25.5-25.7	96.25	3.76	0.00	sand
E4	30.02-30.4	95.84	4.16	0.00	sand
E5	40.3-40.5	98.51	1.49	0.00	sand
E6	44.5-46.4	97.47	2.53	0.00	sand
E7	69	62.05	20.55	17.40	sandy loam
E8	78	40.92	31.36	27.72	clay loam
E9	81-82	31.97	42.98	25.05	loam
E10	93	6.68	67.11	26.21	silt loam

USDA particle-size breaks: sand 0.05–2.0 mm, silt 0.002–0.05 mm, clay <0.002 mm.
Sample ID letter refers to piezometer nest location.
Gravel fraction (>2.0 mm) not included in analysis.

Table B 2. Particle size percentage, Wentworth scale, gravel fraction excluded.

Sample ID	Depth (ft)	% Sand	% Silt	% Clay
B2	8.6-8.8	80.85	19.15	0.00
B3	11.9-12.1	94.49	2.20	3.30
B11	21.1-21.5	88.14	5.46	6.39
B4	31.6-31.8	94.99	5.00	0.00
B5	46.2-46.4	96.72	3.28	0.00
B6	55.6-56.1	94.59	2.62	2.62
B7	60.2-60.5	95.34	4.65	0.00
B8	64.5-64.8	92.96	5.16	1.88
E1	15.2-15.4	93.49	6.51	0.00
E2	20.0-20.2	84.00	16.00	0.00
E3	25.5-25.7	94.37	5.64	0.00
E4	30.0-30.4	93.38	6.61	0.00
E5	40.3-40.5	97.77	2.23	0.00
E6	44.5-46.4	95.40	4.60	0.00

Wentworth particle-size breaks: sand 0.0625–2.0 mm, silt 0.002–0.0625mm, clay <0.002mm.
Sample ID letter refers to piezometer nest location.
Gravel fraction (>2.0 mm) not included in analysis.

Table B 3. Particle size percentage, Wentworth scale, gravel fraction included.

Sample ID	Depth (ft)	% Gravel	% Sand	% Silt	% Clay
B2	8.6-8.8	0.80	80.20	19.00	0.00
B3	11.9-12.1	56.61	42.89	1.00	1.50
B11	21.1-21.5	13.99	75.81	4.70	5.50
B4	31.6-31.8	0.10	94.90	5.00	0.00
B5	46.2-46.4	1.02	95.73	3.25	0.00
B6	55.6-56.1	80.98	18.02	0.50	0.50
B7	60.2-60.5	59.15	38.95	1.90	0.00
B8	64.5-64.8	36.08	59.42	3.30	1.20
E1	15.2-15.4	38.57	57.43	4.00	0.00
E2	20.0-20.2	73.75	22.05	4.20	0.00
E3	25.5-25.7	73.41	25.09	1.50	0.00
E4	30.02-30.4	47.09	49.41	3.50	0.00
E5	40.3-40.5	46.25	52.55	1.20	0.00
E6	44.5-46.4	13.13	82.87	4.00	0.00

Wentworth particle-size breaks: gravel >2.0mm, sand 0.0625 – 2.0 mm, silt 0.002 – 0.0625 mm, clay <0.002mm.

Sample ID letter refers to piezometer nest location.

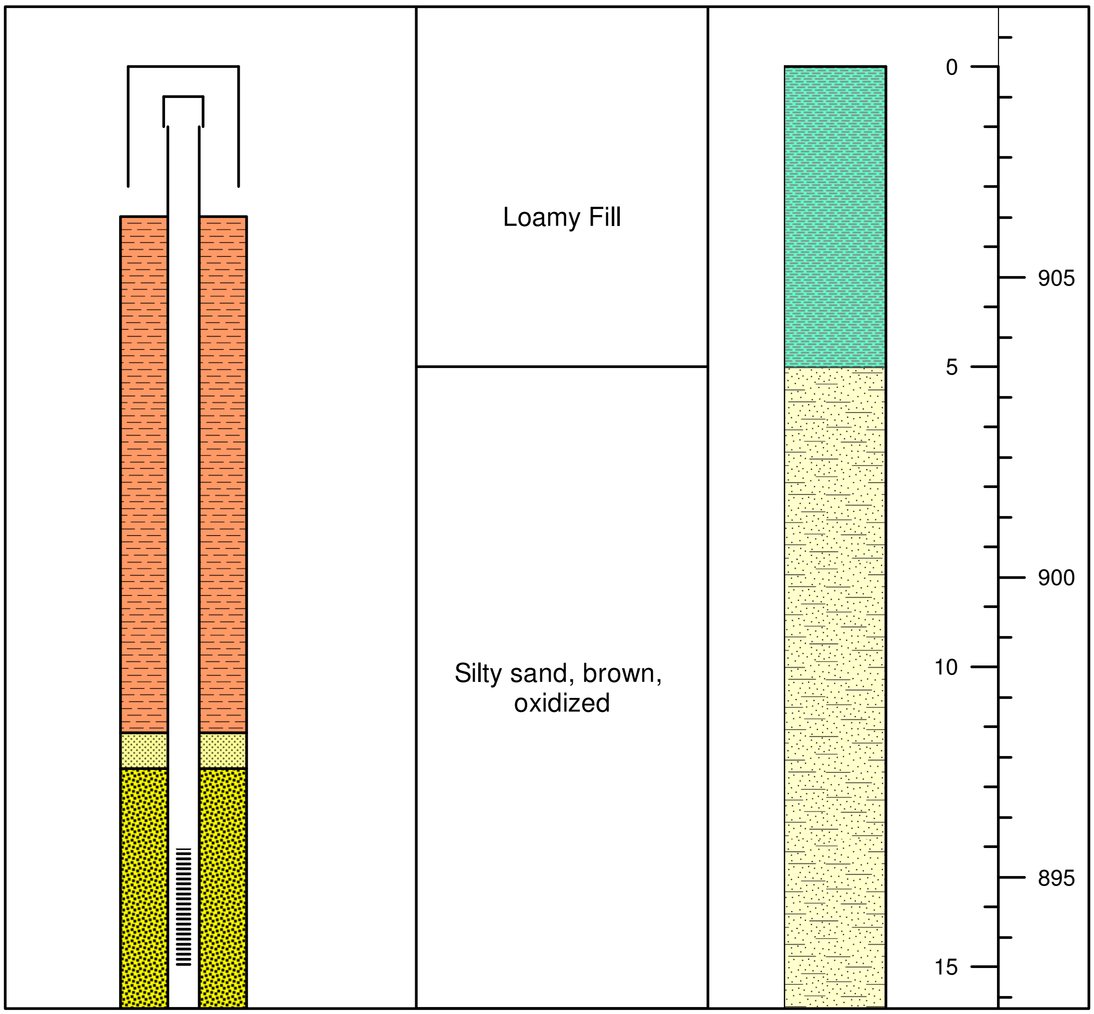
APPENDIX C

WELL LOGS

Ada Hayden Heritage Park Monitoring Well

A 15

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



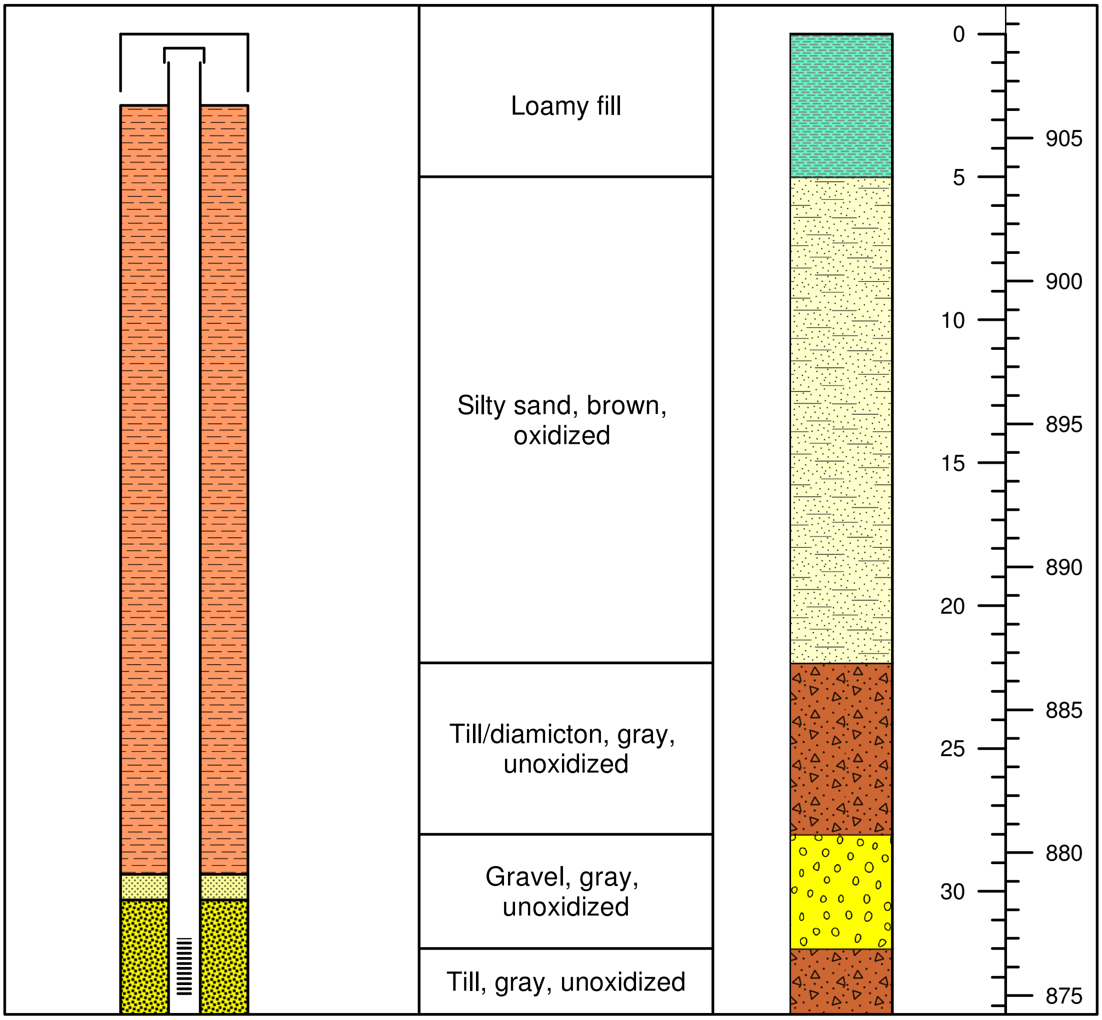
Date Drilled:	3/28/06	Easting (UTM, NAD 83):	448327.117082
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4658103.146640
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.512
Driller:	Dennis Auld	Drilling Method:	Auger

Note:
Please refer to separate diagram for details on well construction.

Ada Hayden Heritage Park Monitoring Well

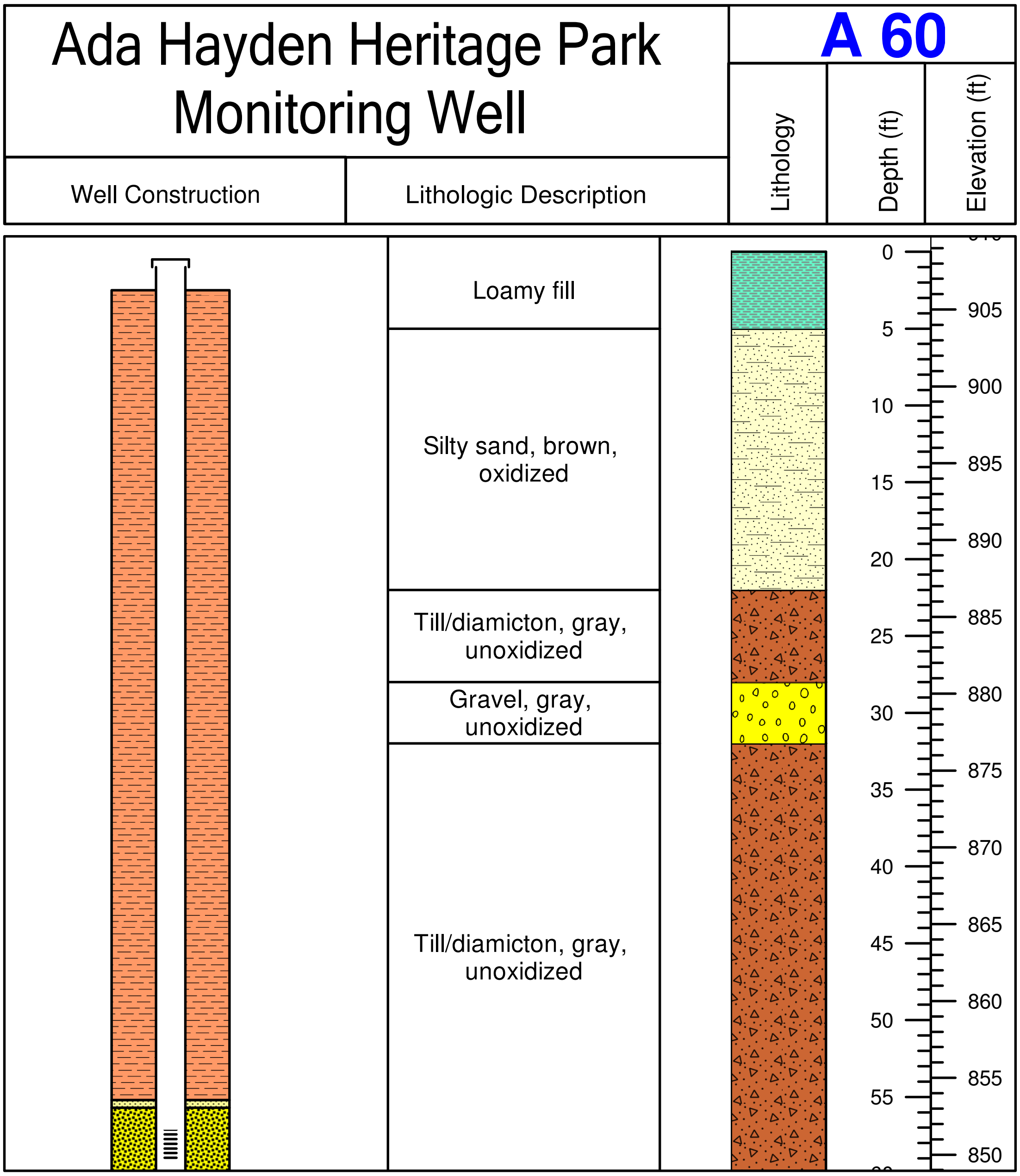
A 35

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)

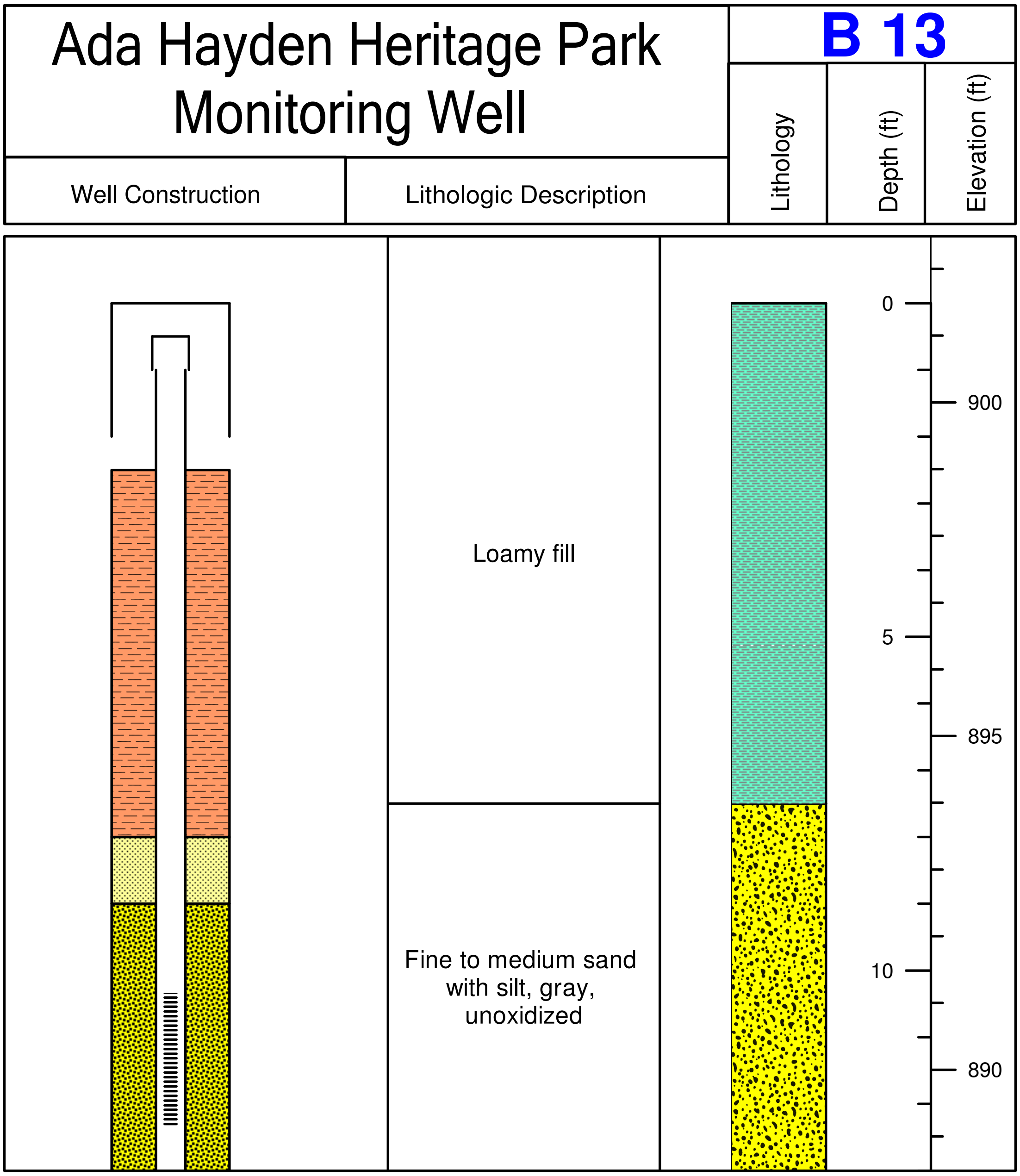


Date Drilled:	3/28/26	Easting (UTM, NAD 83):	448325.208513
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4658103.414010
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.646
Driller:	Dennis Auld	Drilling Method:	Auger

Note:
Please refer to separate diagram for details on well construction.



Date Drilled:	3/28/06	Easting (UTM, NAD 83):	448323.378923	Note: *Please refer to separate diagram for details on well construction.*
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4658103.431080	
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.759	
Driller:	Dennis Auld	Drilling Method:	Auger	

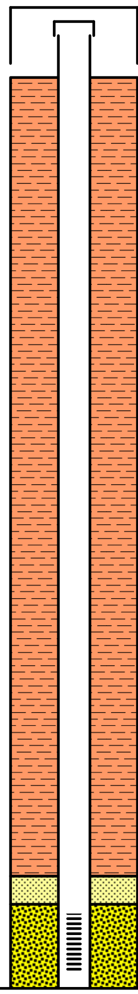


Date Drilled:	3/24/06	Easting (UTM, NAD 83):	447847.854643	Note:
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657855.291270	*Please refer to separate diagram for details on well construction.*
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	901.487	
Driller:	Dennis Auld	Drilling Method:	Auger	

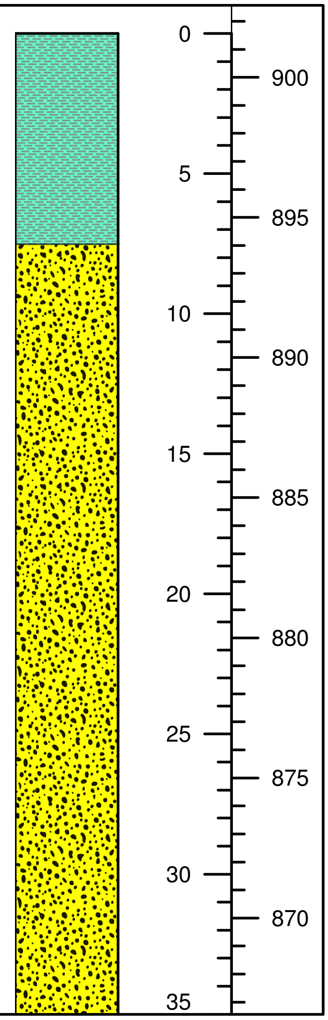
Ada Hayden Heritage Park Monitoring Well

B 35

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)

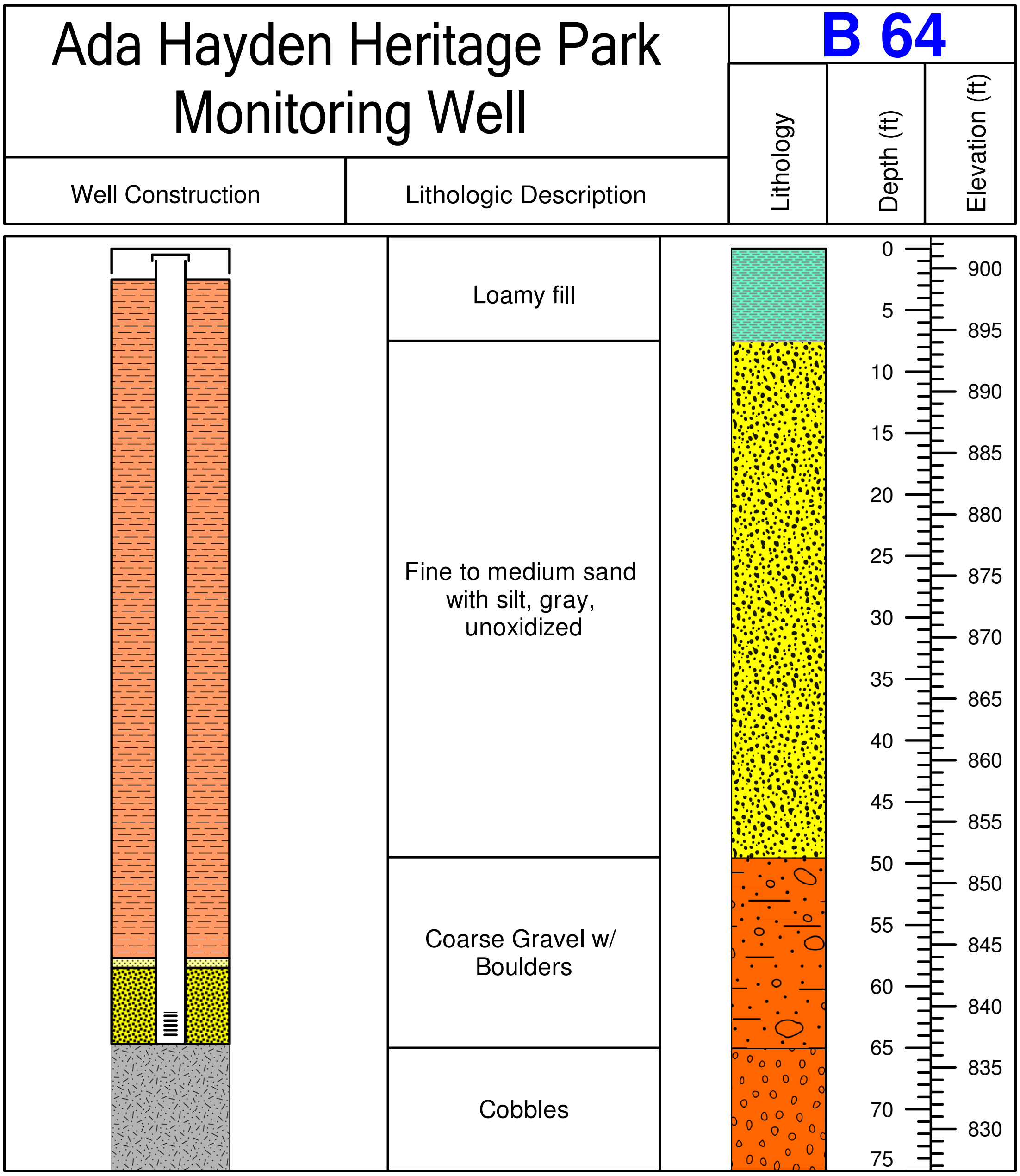


Lithologic Description
Loamy fill
Fine to medium sand with silt, gray, unoxidized



Date Drilled:	4/12/06	Easting (UTM, NAD 83):	447847.850681
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657856.754430
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	901.566
Driller:	Dennis Auld	Drilling Method:	Auger

Note:
Please refer to separate diagram for details on well construction.

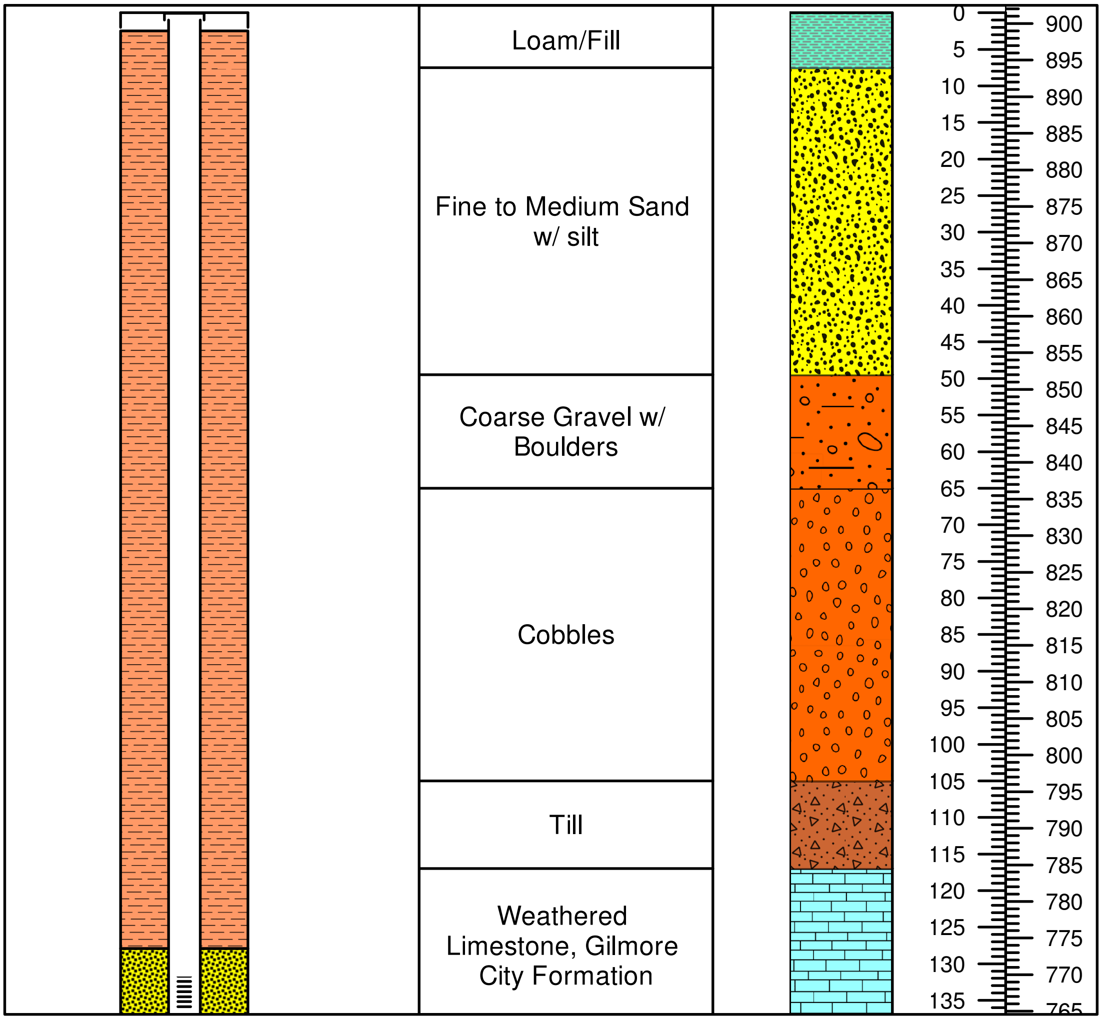


Date Drilled:	3/23/06	Easting (UTM, NAD 83):	447847.869375	Note:
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657853.898420	*Please refer to separate diagram for details on well construction.*
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	901.607	
Driller:	Dennis Auld	Drilling Method:	Auger	

Ada Hayden Heritage Park Monitoring Well

B 138

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



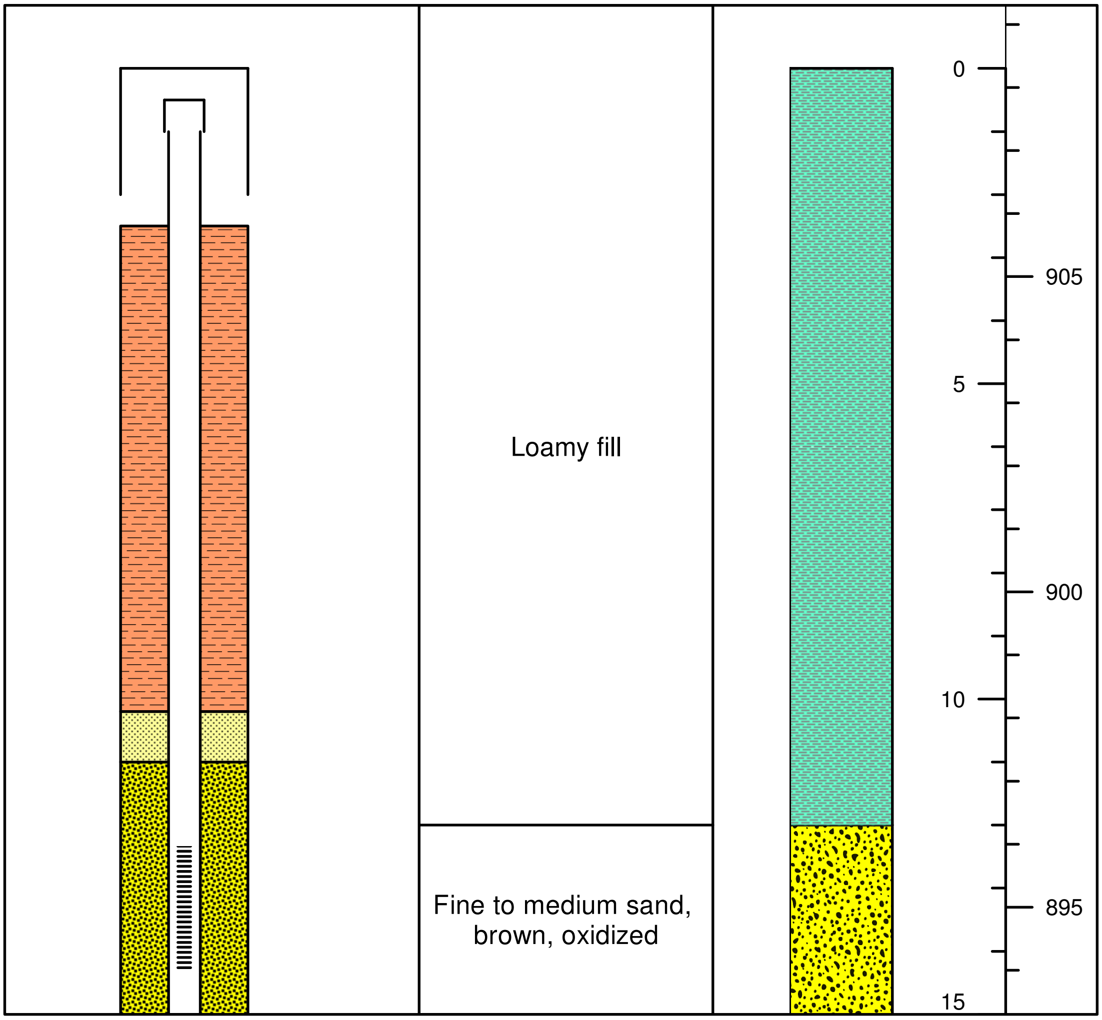
Date Drilled:	4/11/06	Easting (UTM, NAD 83):	447847.819879
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657858.369800
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	901.483
Driller:	Dennis Auld	Drilling Method:	Mud Rotary

Note:
Please refer to separate diagram for details on well construction.

Ada Hayden Heritage Park Monitoring Well

C 15

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)

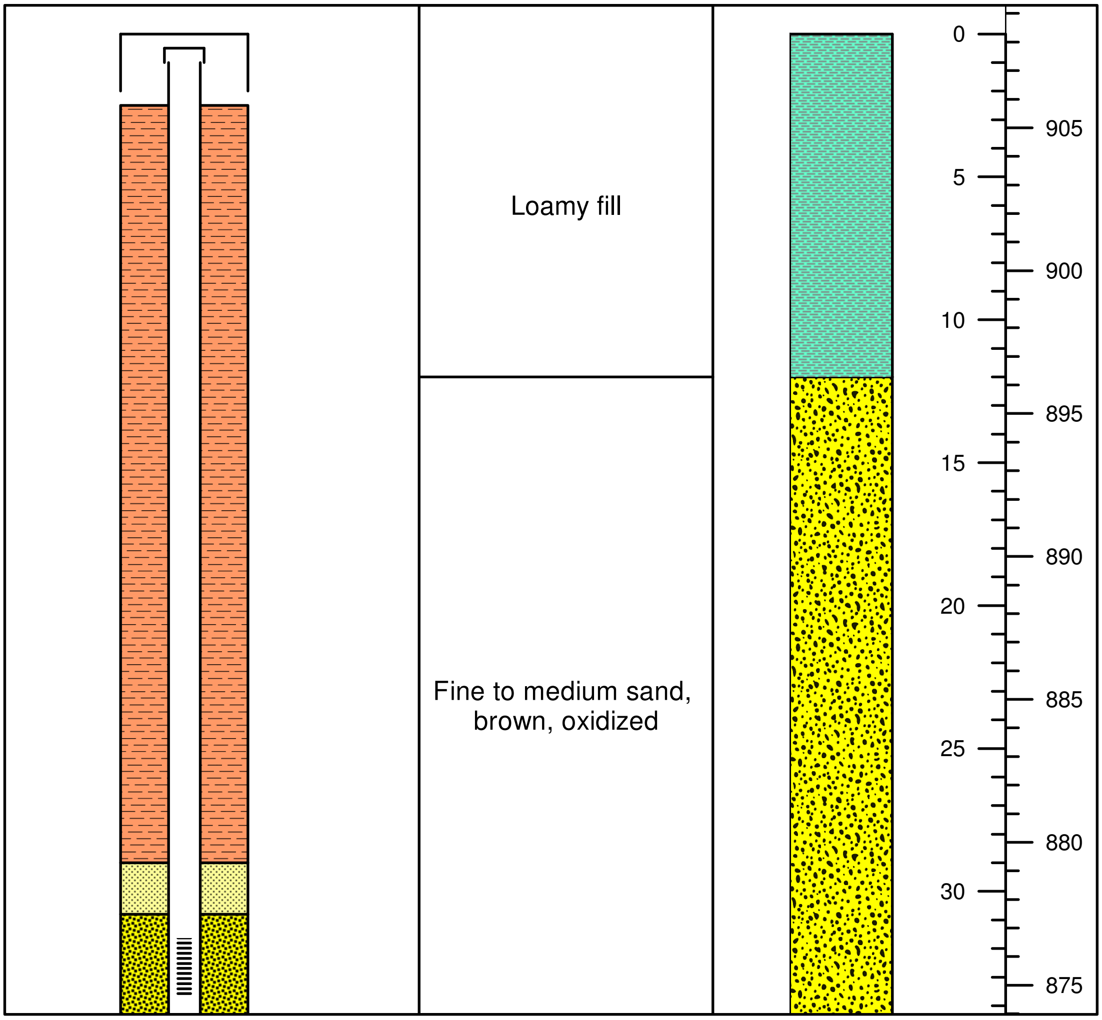


Date Drilled:	3/29/06	Easting (UTM, NAD 83):	447583.670355	Note:
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657049.795780	*Please refer to separate diagram for details on well construction.*
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.302	
Driller:	Dennis Auld	Drilling Method:	Auger	

Ada Hayden Heritage Park Monitoring Well

C 35

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)

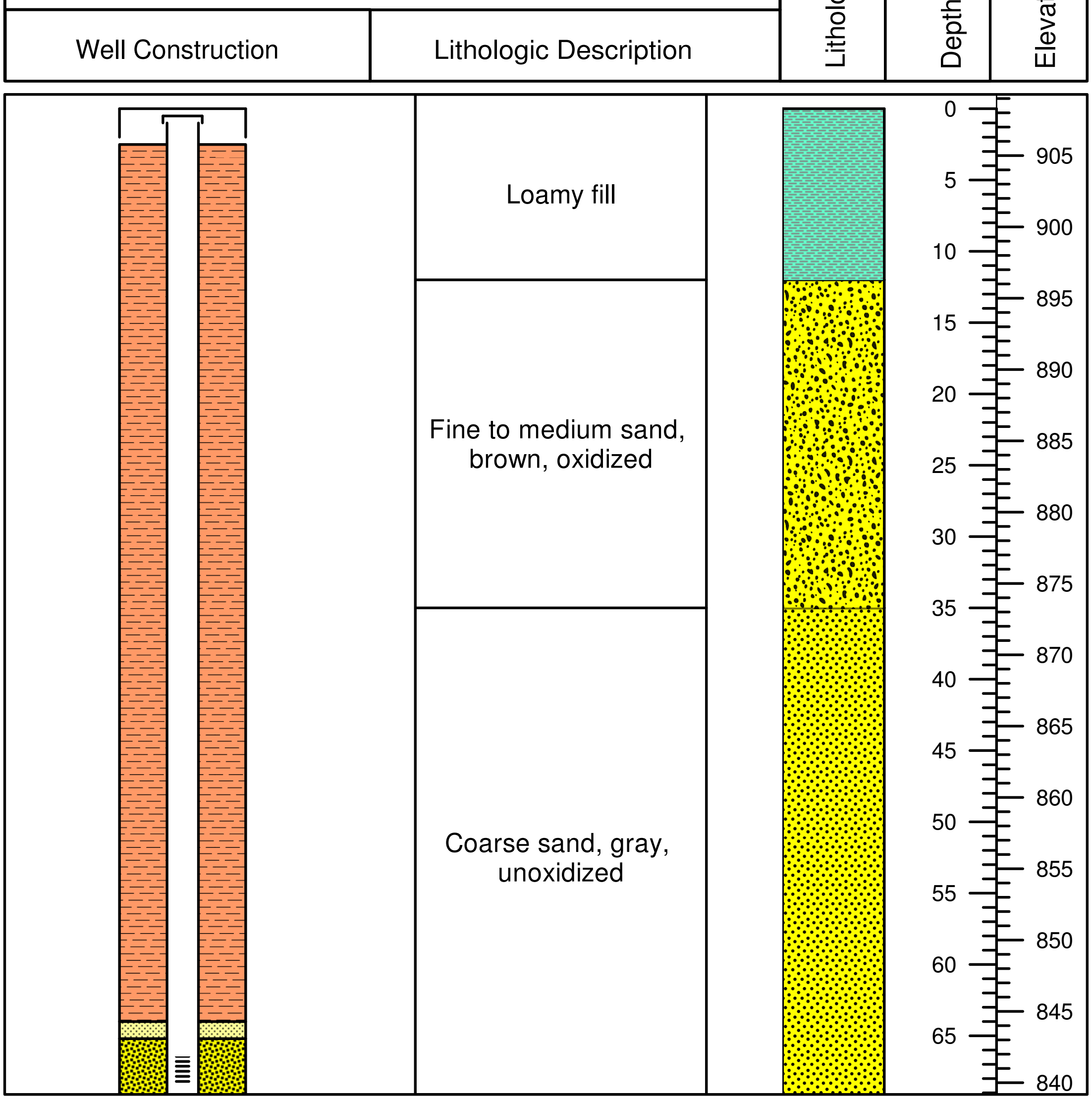


Date Drilled:	3/29/06	Easting (UTM, NAD 83):	447585.299465
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657050.146430
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.282
Driller:	Dennis Auld	Drilling Method:	Auger

Note:
Please refer to separate diagram for details on well construction.

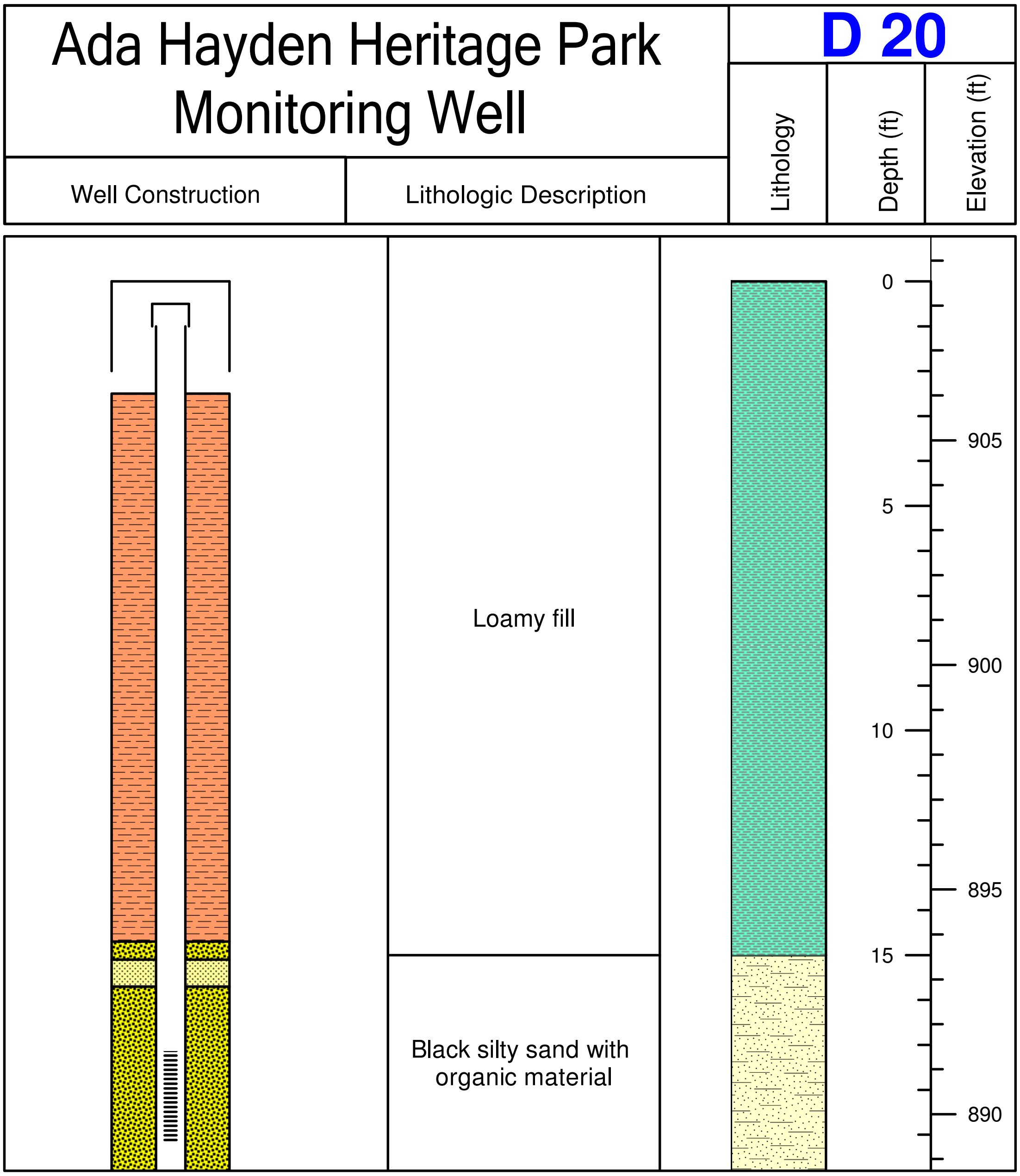
Ada Hayden Heritage Park Monitoring Well

C 70



Date Drilled:	3/29/06	Easting (UTM, NAD 83):	447587.060854
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657050.556640
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.281
Driller:	Dennis Auld	Drilling Method:	Auger

Note:
Please refer to separate diagram for details on well construction.

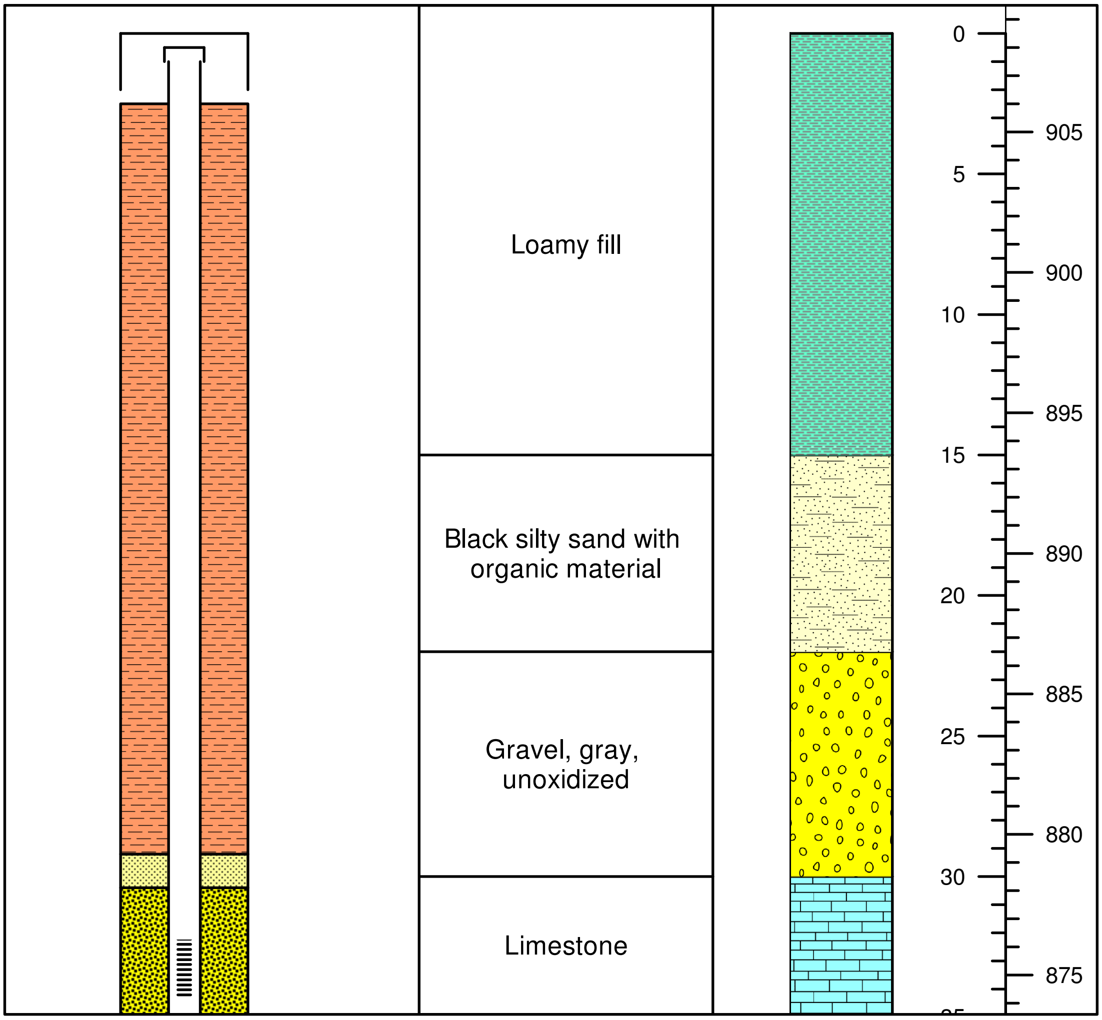


Date Drilled:	3/30/06	Easting (UTM, NAD 83):	448342.278576	Note:
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4656854.796970	*Please refer to separate diagram for details on well construction.*
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.540	
Driller:	Dennis Auld	Drilling Method:	Auger	

Ada Hayden Heritage Park Monitoring Well

D 35

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



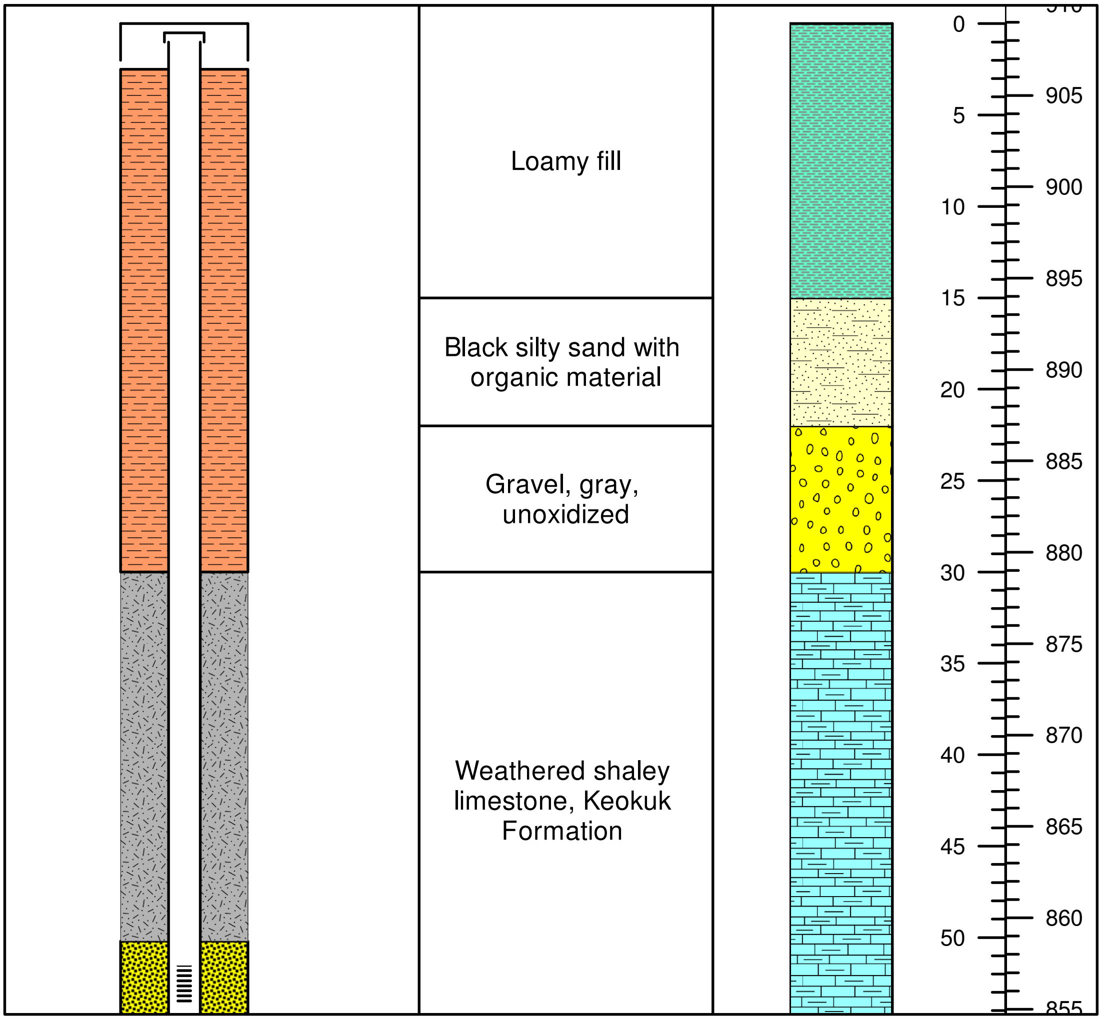
Date Drilled:	3/30/06	Easting (UTM, NAD 83):	448343.772834
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4656855.535670
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.501
Driller:	Dennis Auld	Drilling Method:	Auger

Note:
Please refer to separate diagram for details on well construction.

Ada Hayden Heritage Park Monitoring Well

D 55

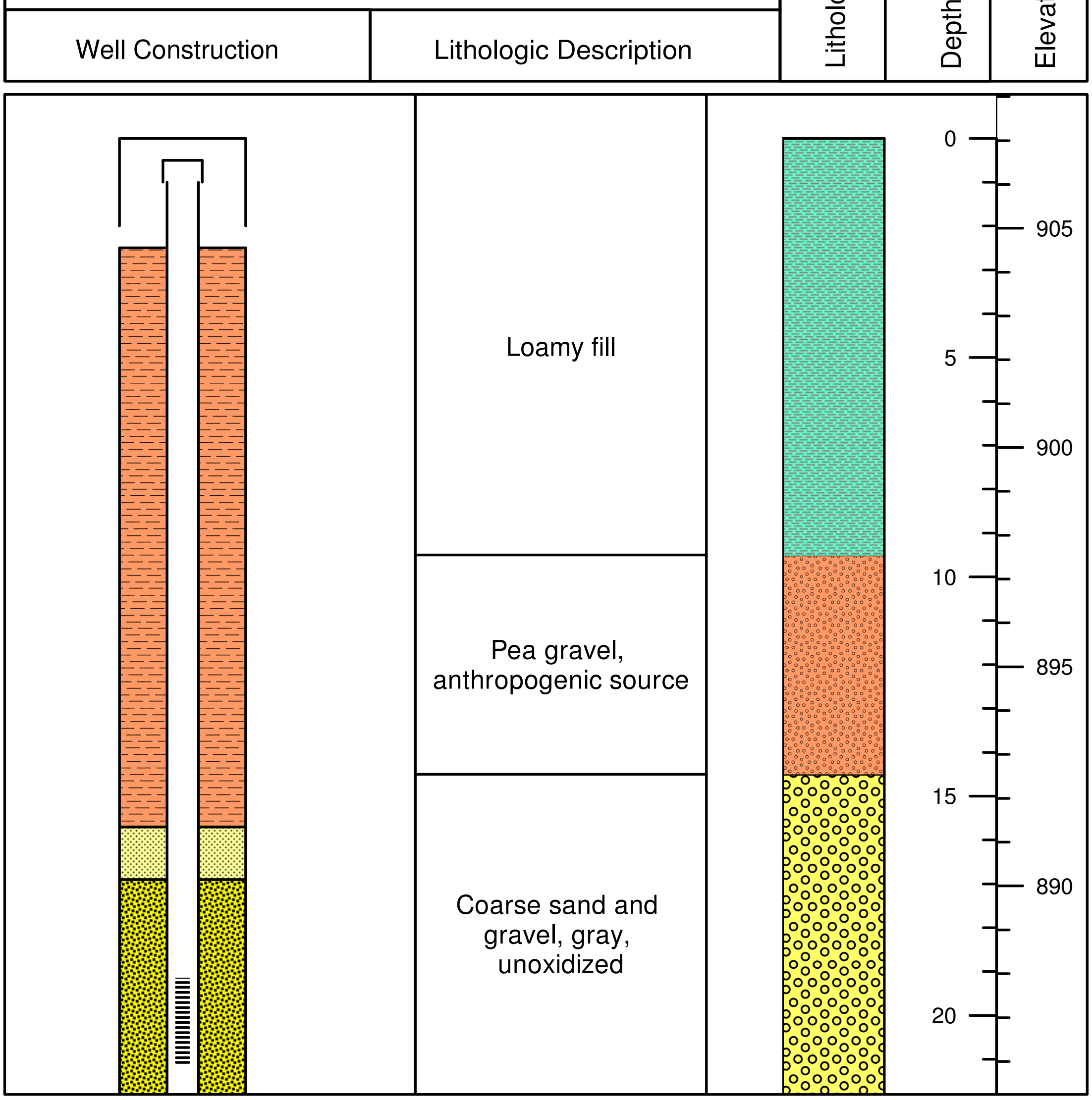
Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



Date Drilled:	4/06/06	Easting (UTM, NAD 83):	448340.521952	Note: *Please refer to separate diagram for details on well construction.*
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4656853.844980	
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	908.922	
Driller:	Dennis Auld	Drilling Method:	Mud Rotary	

Ada Hayden Heritage Park Monitoring Well

E 22



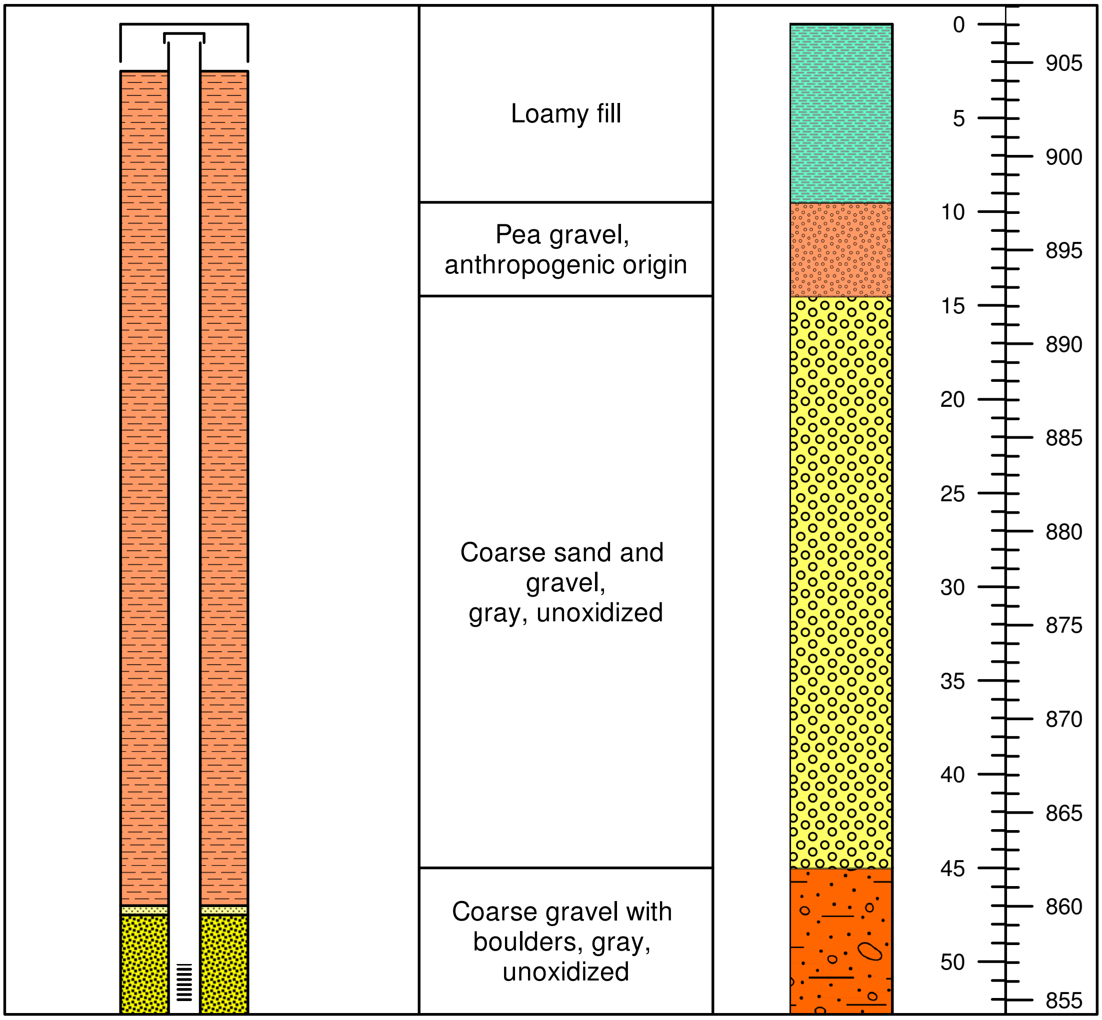
Date Drilled:	4/03/2006	Easting (UTM, NAD 83):	448418.396019
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657445.956650
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	907.050
Driller:	Dennis Auld	Drilling Method:	Auger

Note:
Please refer to separate diagram for details on well construction.

Ada Hayden Heritage Park Monitoring Well

E 53

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)

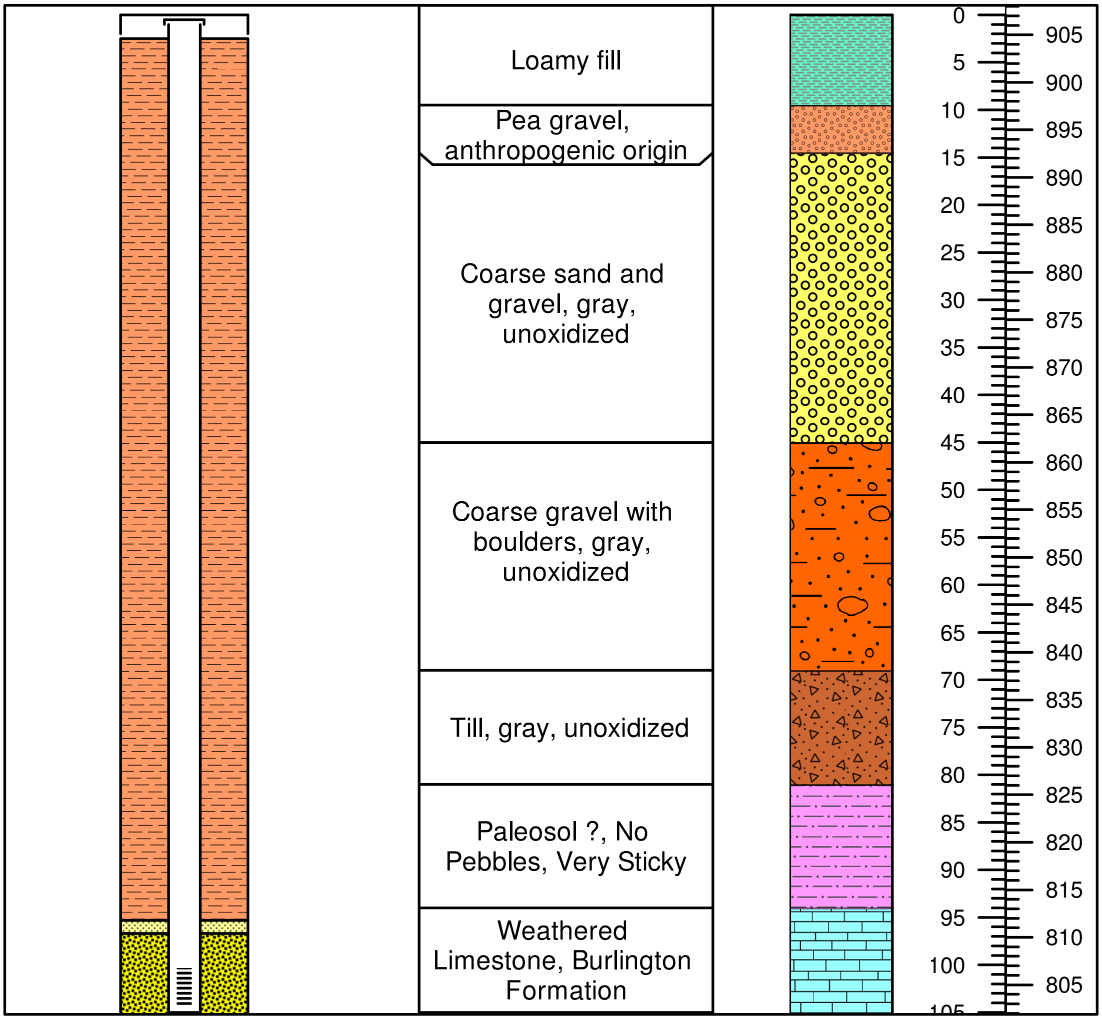


Date Drilled:	3/31/2006	Easting (UTM, NAD 83):	448418.149267	Note:
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657444.136020	*Please refer to separate diagram for details on well construction.*
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	907.042	
Driller:	Dennis Auld	Drilling Method:	Auger	

Ada Hayden Heritage Park Monitoring Well

E 105

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



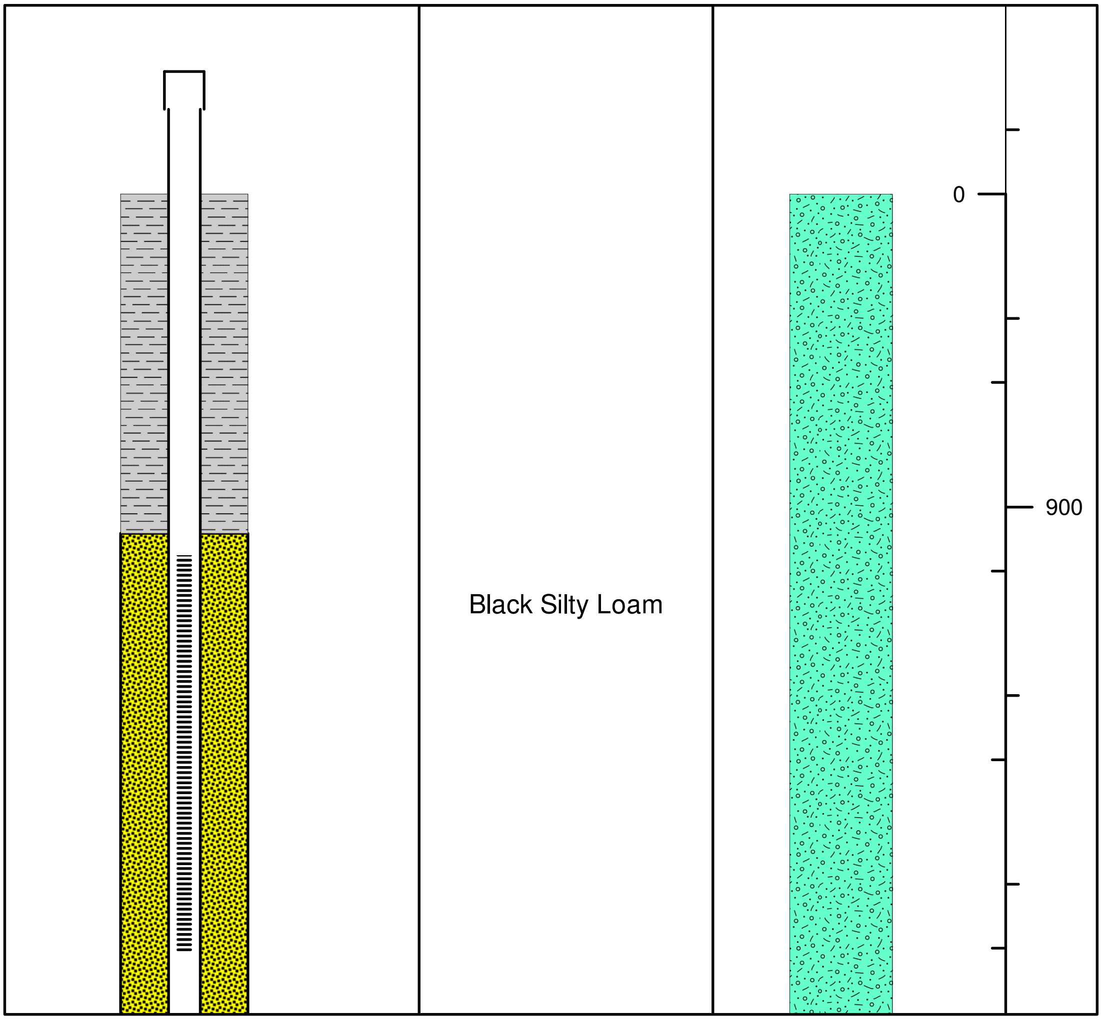
Date Drilled:	4/13/2006	Easting (UTM, NAD 83):	448417.762976
Geologist:	Evan Christainson	Northing (UTM, NAD 83):	4657441.481340
Drilling Contractor:	Aquadrill	Elevation (ft, top of riser):	907.101
Driller:	Dennis Auld	Drilling Method:	Mud Rotary

Note:
Please refer to separate diagram for details on well construction.

Ada Hayden Heritage Park Monitoring Well (v.1.0)

F5

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



Date Drilled: 8/4/06
Geologist: Evan Christianson
Drilling Contractor:
Driller: Evan Christianson

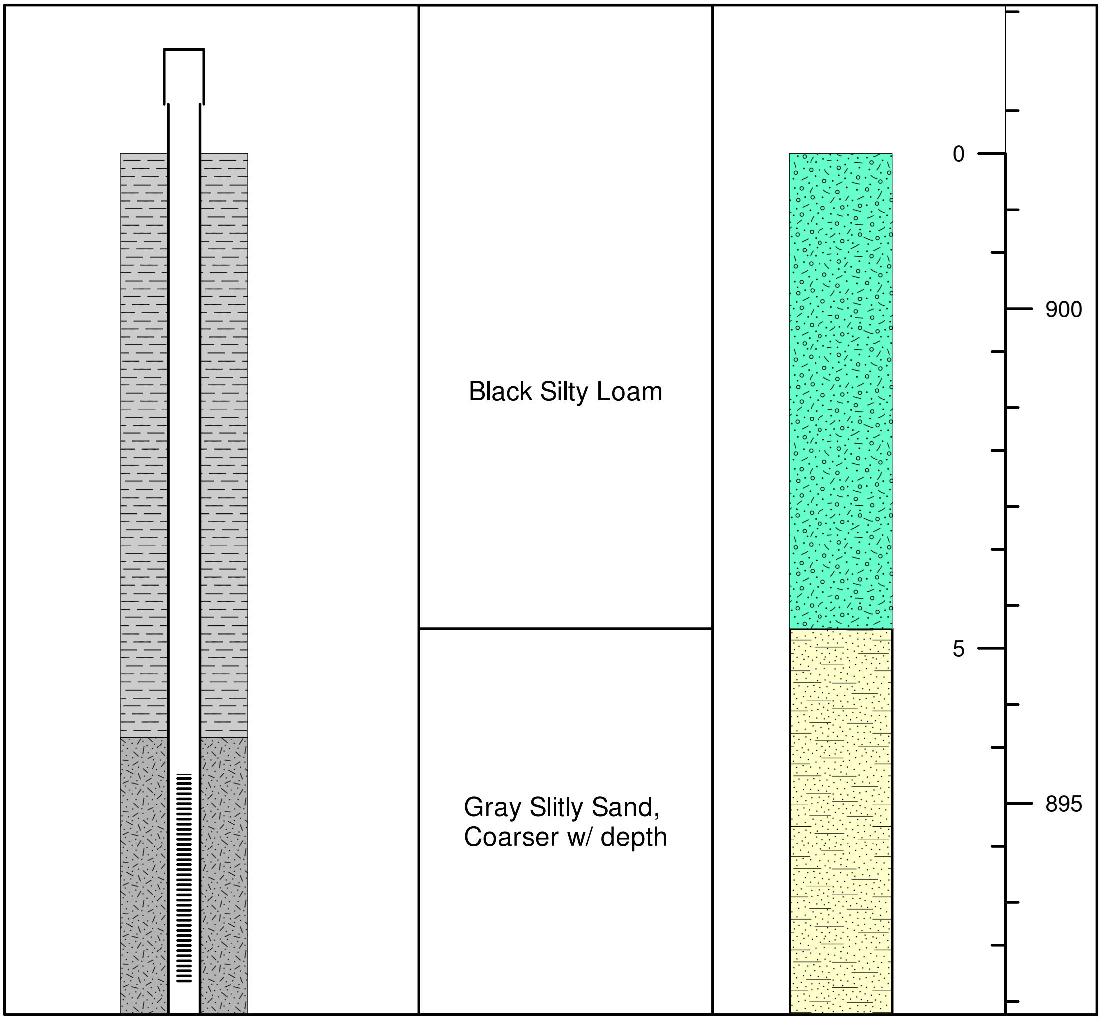
Easting (UTM, NAD 83): 447760.19
Northing (UTM, NAD 83): 4657830.26
Elevation (ft, ground surface): 901.66
Drilling Method: Hand Auger

Note:
Please refer to separate diagram for details on well construction.

Ada Hayden Heritage Park Monitoring Well (v.1.0)

F9

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



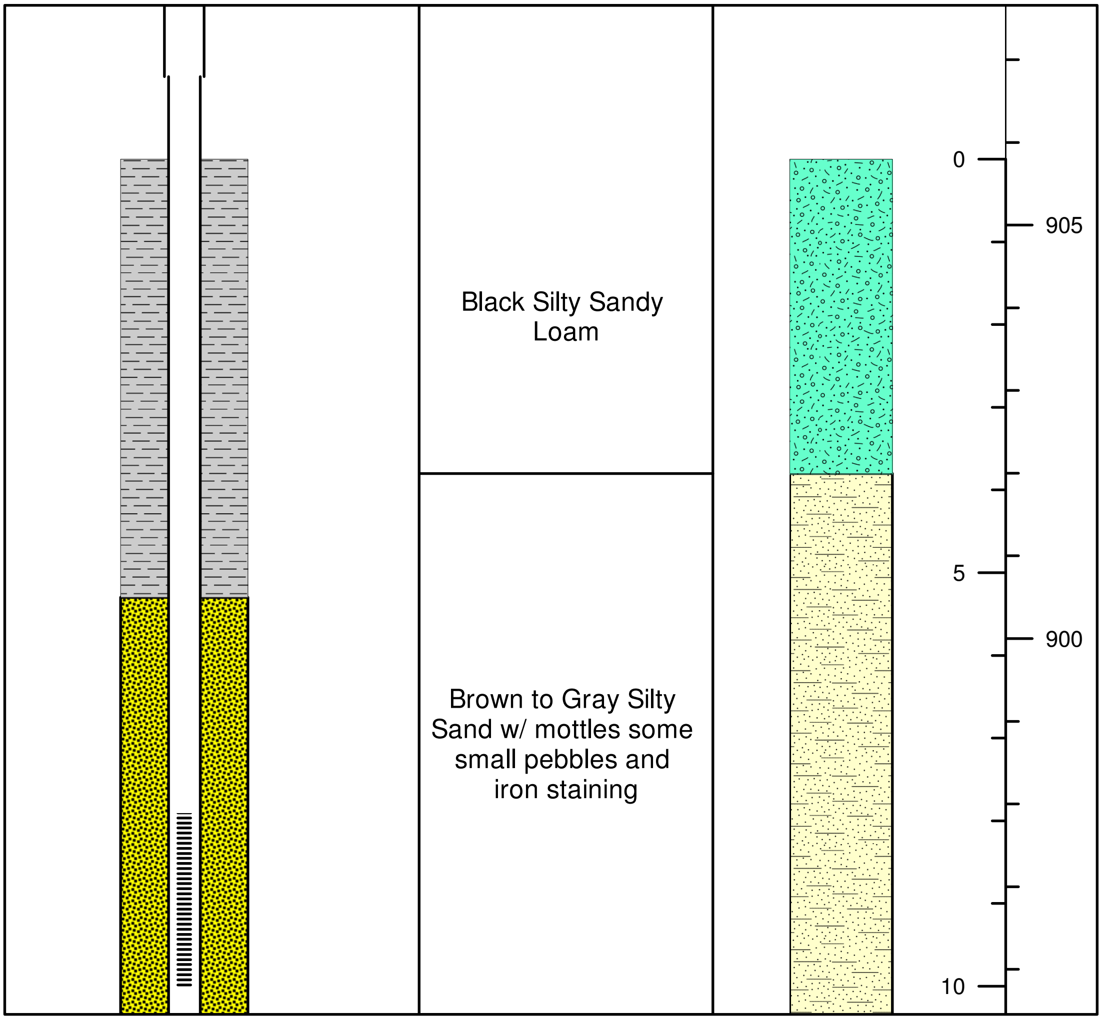
Date Drilled:	8/4/06	Easting (UTM, NAD 83):	447759.92
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	447759.92
Drilling Contractor:		Elevation (ft, ground surface):	901.567
Driller:	Evan Christianson	Drilling Method:	Hand Auger

Note:
Please refer to separate diagram for details on well construction.

Ada Hayden Heritage Park Monitoring Well (v.1.0)

H10

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



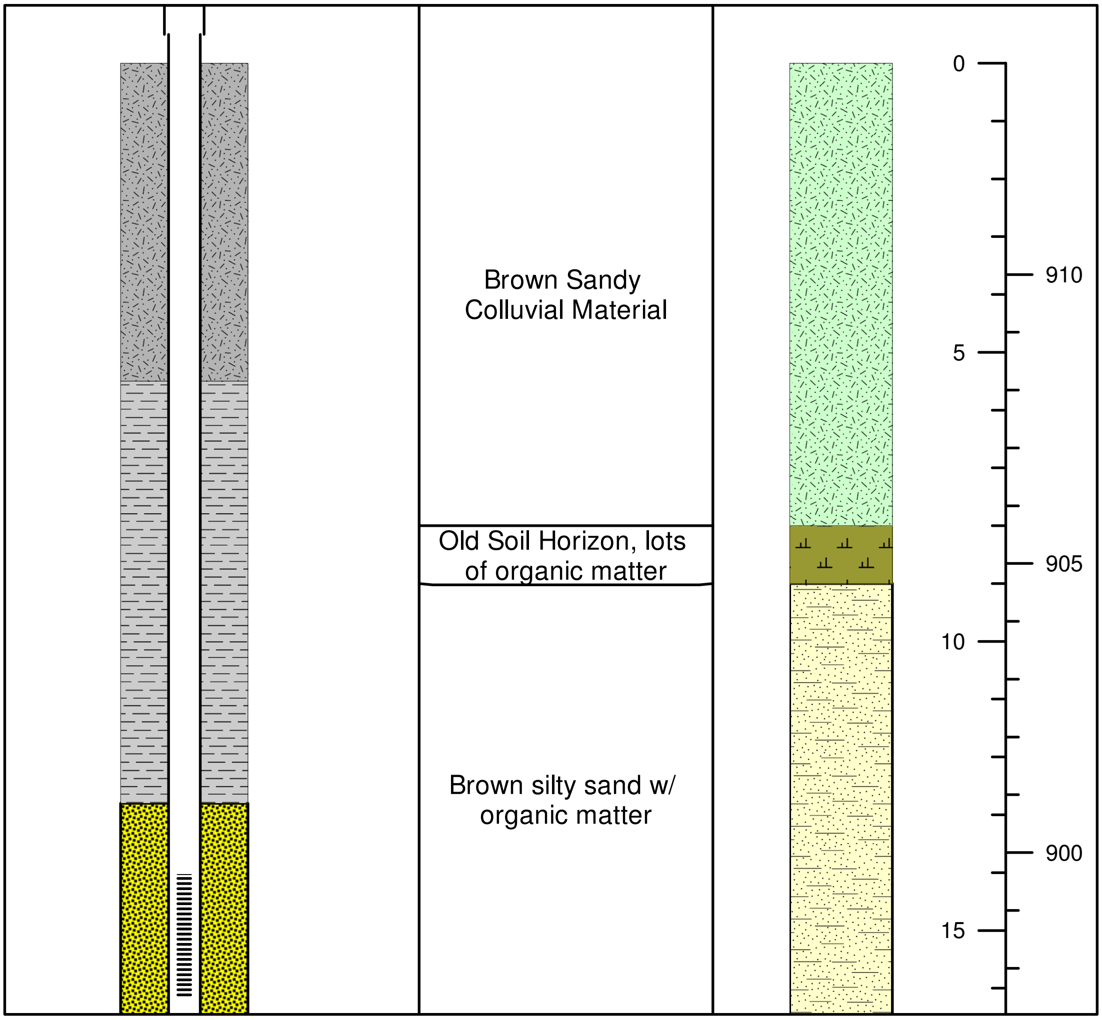
Date Drilled:	8/7/06	Easting (UTM, NAD 83):	447348.32
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657389.81
Drilling Contractor:		Elevation (ft, ground surface):	905.797
Driller:	Evan Christianson	Drilling Method:	Hand Auger

Note:
Please refer to separate diagram for details on well construction.

Ada Hayden Heritage Park Monitoring Well (v.1.0)

G16

Well Construction	Lithologic Description	Lithology	Depth (ft)	Elevation (ft)



Date Drilled:	8/5/06	Easting (UTM, NAD 83):	447197.27
Geologist:	Evan Christianson	Northing (UTM, NAD 83):	4657722.37
Drilling Contractor:		Elevation (ft, ground surface):	913.654
Driller:	Evan Christianson	Drilling Method:	Hand Auger

Note:
Please refer to separate diagram for details on well construction.

APPENDIX D

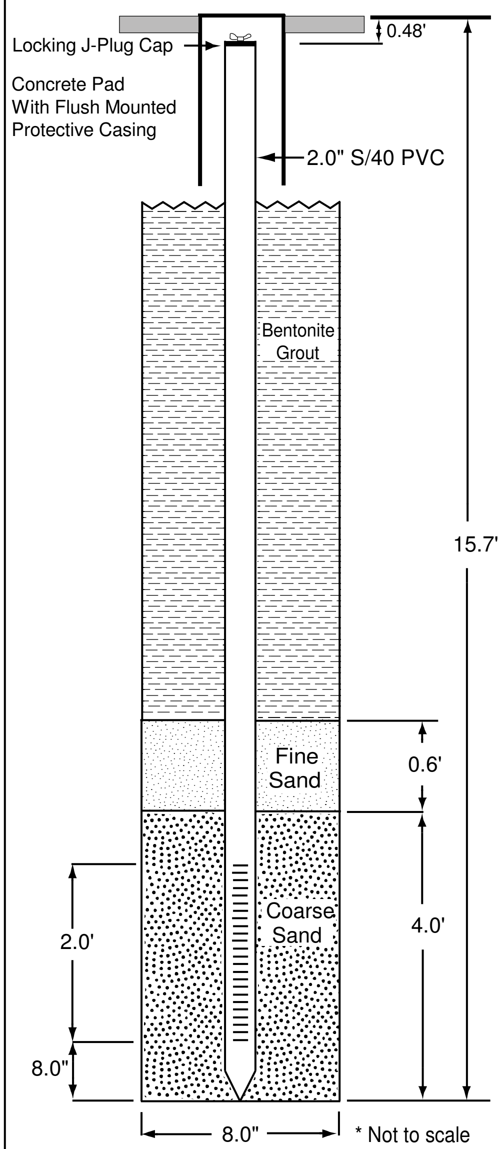
WELL CONSTRUCTION DIAGRAMS

Ada Hayden Heritage Park Well
A-15

Installation Date: 03/28/06
Total Depth: 15.7'
Drilling method: Auger

UTM Northing (NAD 83, Zone 15): 4658103.146640
UTM Easting (NAD 83, Zone 15): 448327.117082

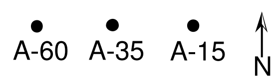
Top of Casing: 908.512 ft
Screen Size: 0.020 slot



* Not to scale

Notes:

Located east of A-35.

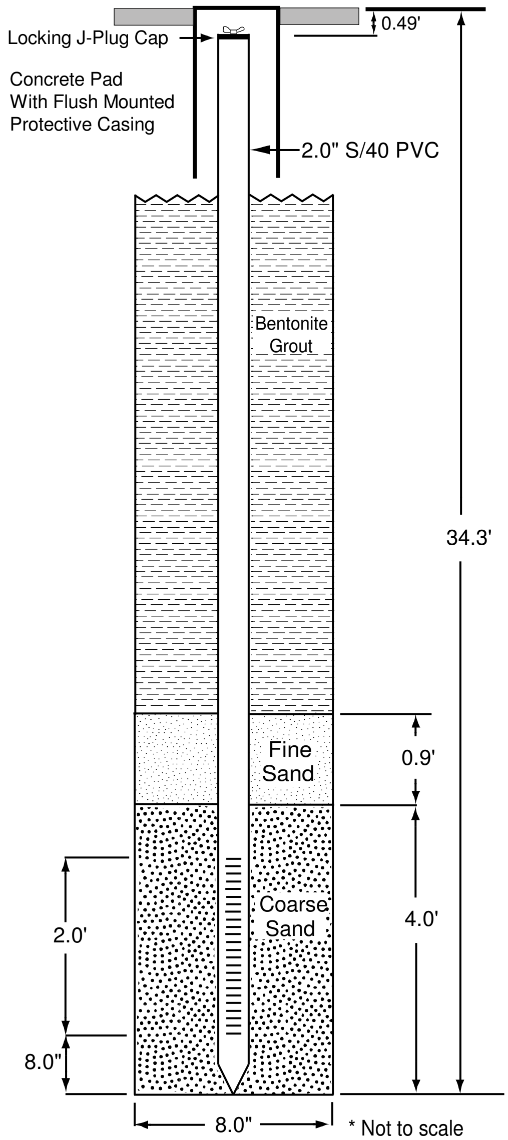


Ada Hayden Heritage Park Well
A-35

Installation Date: 03/28/06
Total Depth: 34.3'
Drilling method: Auger

UTM Northing (NAD 83, Zone 15): 4658103.414010
UTM Easting (NAD 83, Zone 15): 448325.208513

Top of Casing: 908.646 ft
Screen Size: 0.020 slot



Notes:

Located east of A-60

A-60 A-35 A-15 N

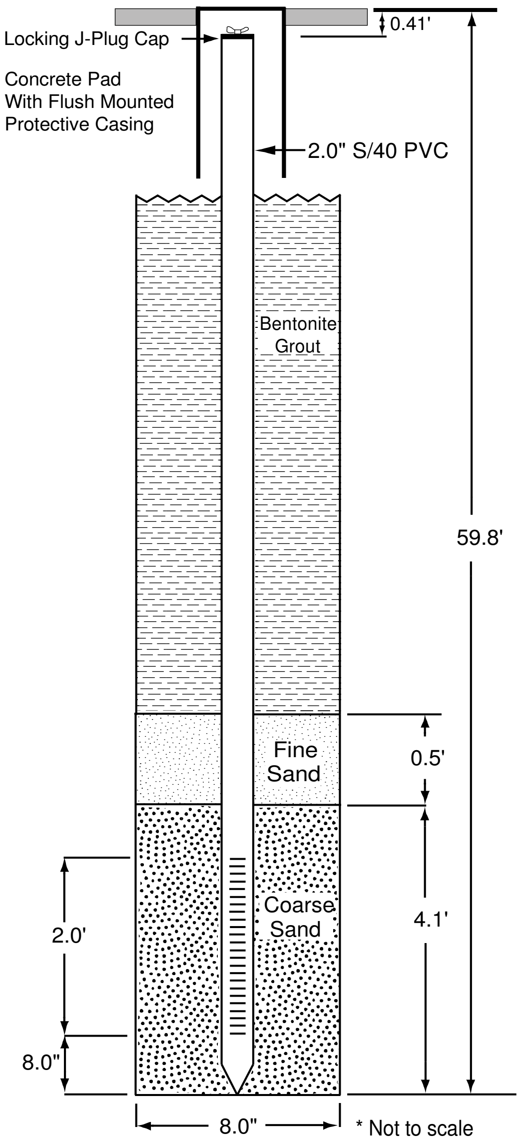
Hard to tell depth to top of fine sand, much of it remained suspended. Put in whole 50 lbs bag.

Ada Hayden Heritage Park Well
A-60

Installation Date: 03/28/06
Total Depth: 59.8'
Drilling method: Auger

UTM Northing (NAD 83, Zone 15): 4658103.431080
UTM Easting (NAD 83, Zone 15): 448323.378923

Top of Casing: 908.759 ft
Screen Size: 0.020 slot



Notes:

Located south of A-35

A-60 A-35 A-15 N

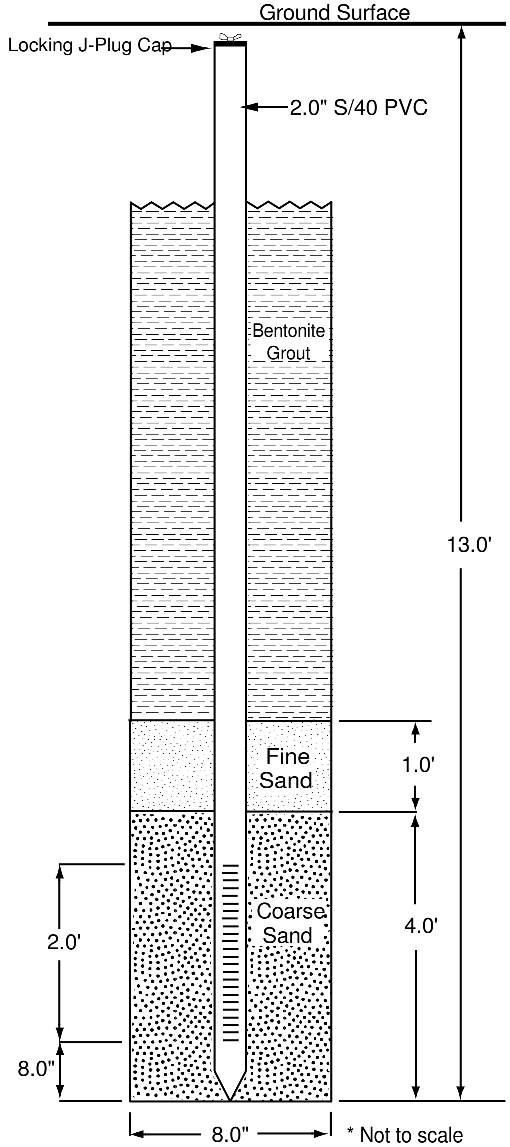
Hard to tell depth to top of fine sand, much of it remained suspended. Put in whole 50 lbs bag.

Ada Hayden Heritage Park Well
B-13

Installation Date: 03/24/06
Total Depth: 13.0'
Drilling method: Auger

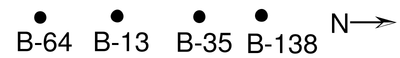
UTM Northing (NAD 83, Zone 15): 4657855.291270
UTM Easting (NAD 83, Zone 15): 447847.854643

Survey Elevation: 901.487 ft
Screen Size: .020 slot



Notes:

Located north of B-64

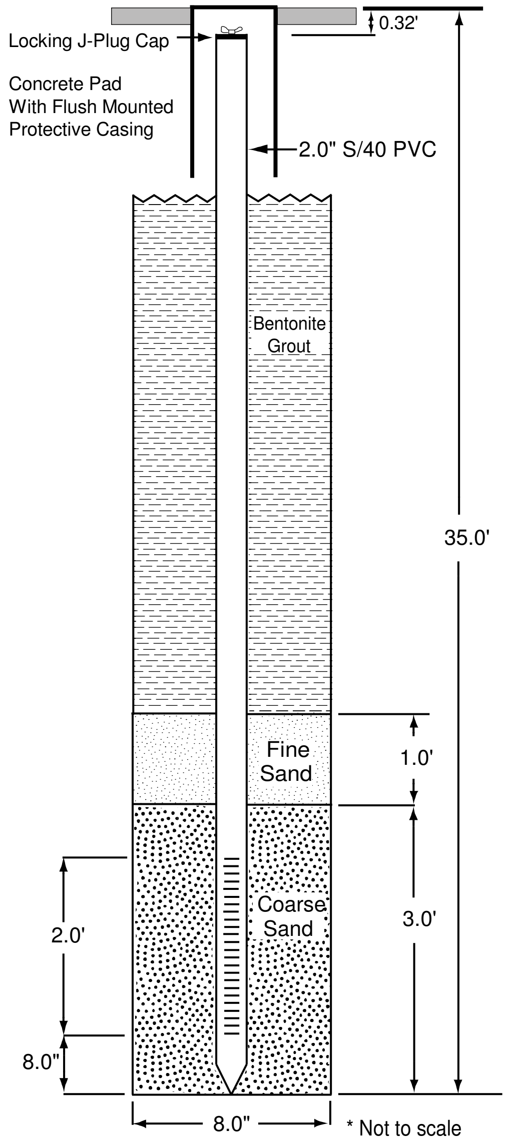


Ada Hayden Heritage Park Well
B-35

Installation Date: 04/12/06
Total Depth: 35.0'
Drilling method: Auger

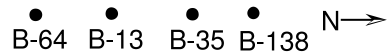
UTM Northing (NAD 83, Zone 15): 4657856.754430
UTM Easting (NAD 83, Zone 15): 447847.850681

Top of Casing: 901.566 ft
Screen Size: 0.020 slot



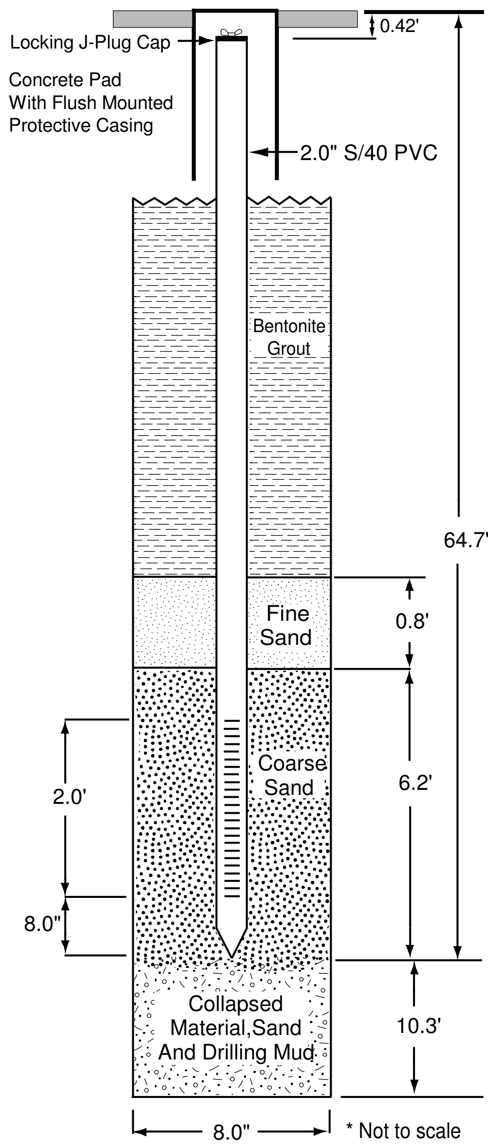
Notes:

Located north of B-13



Ada Hayden Heritage Park Well
B-64

Installation Date: 03/23/06 UTM Northing (NAD 83, Zone 15): 4657853.898420 Top of Casing: 901.607 ft
Total Depth: 64.7' UTM Easting (NAD 83, Zone 15): 447847.869375 Screen Size: 0.020 slot
Drilling method: Auger



Notes:

Located south of B-13

B-64 B-13 B-35 B-138 N→

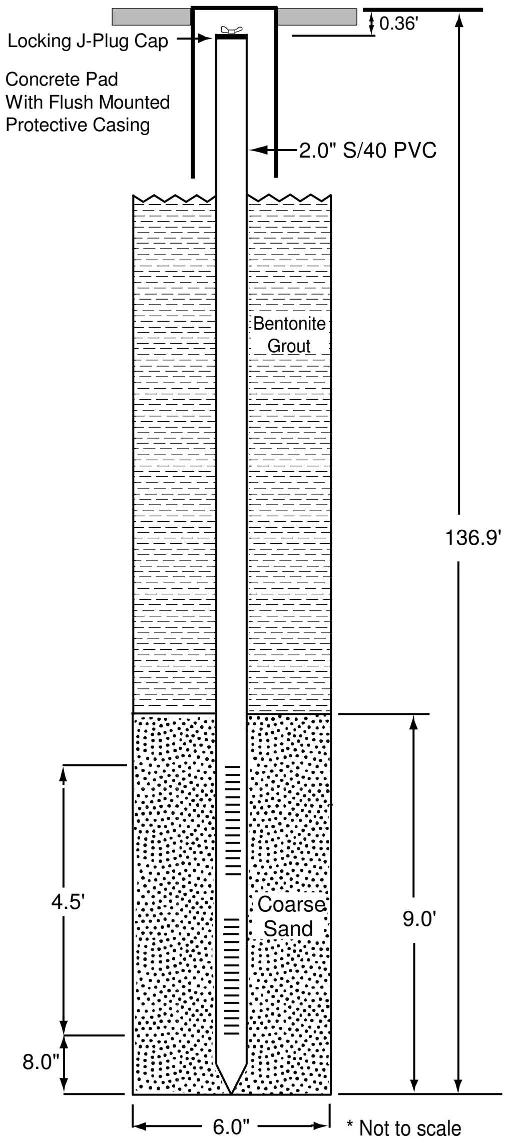
Drilled with augers at first then switched to mud rotary to try and get through boulders. Drilled to 75 ft then pulled up to 64.7 ft to set the well. Most of the hole below 64.7 ft filled in on its own with gravel the rest was filled with sand. Sand may have mixed with drilling mud that was already in the hole.

Ada Hayden Heritage Park Well
B-138

Installation Date: 04/11/06 | UTM Northing (NAD 83, Zone 15): 4657858.369800 | Top of Casing: 901.483 ft

Total Depth: 136.9' | UTM Easting (NAD 83, Zone 15): 447847.819879 | Screen Size: 0.020 slot

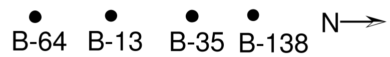
Drilling method: Mud Rotary



* Not to scale

Notes:

Located north of B-35

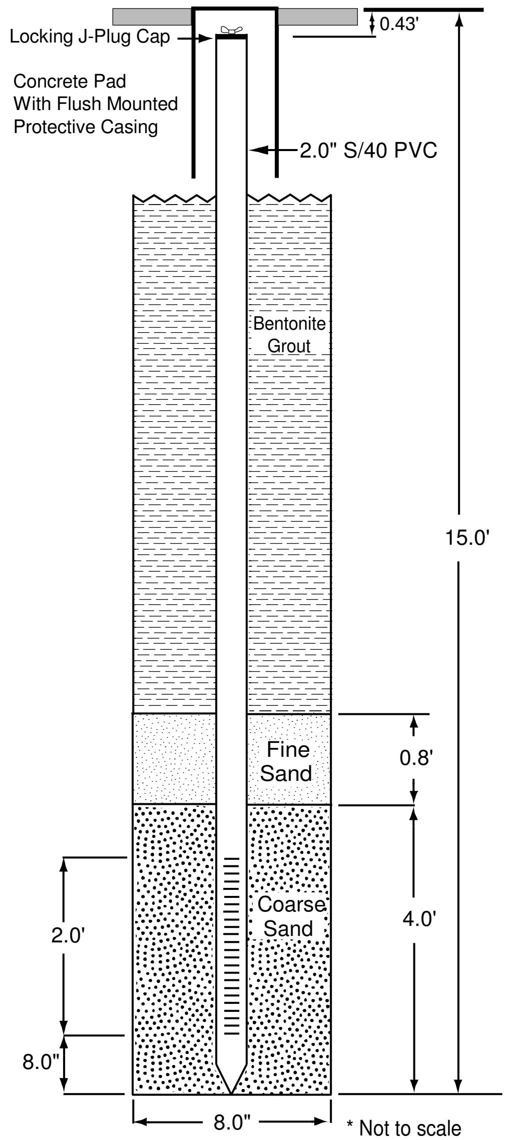


Used tremie pipe to put in sand pack. Recirculated clean water until water returning cleared up and fines removed. Pumped sand and clean water down tremie pipe to install sand pack.

Took more mud than it should have. Hole seems to have been washed out somewhere.

Ada Hayden Heritage Park Well
C-15

Installation Date: 03/29/06	UTM Northing (NAD 83, Zone 15): 4657049.795780	Top of Casing: 908.302 ft
Total Depth: 15.0'	UTM Easting (NAD 83, Zone 15): 447583.670355	Screen Size: 0.020 slot
Drilling method: Auger		



* Not to scale

Notes:

Located west of C-35

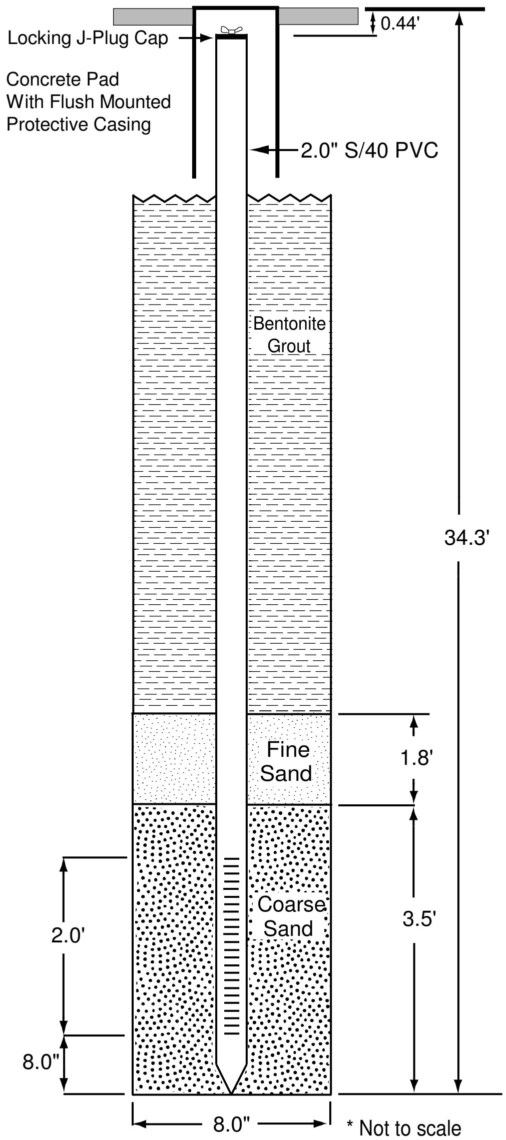
C-15 C-35 C-70 N

Ada Hayden Heritage Park Well
C-35

Installation Date: 03/29/06
Total Depth: 34.3'
Drilling method: Auger

UTM Northing (NAD 83, Zone 15): 4657050.146430
UTM Easting (NAD 83, Zone 15): 447585.299465

Top of Casing: 908.282 ft
Screen Size: 0.020 slot



Notes:

Located west of C-70

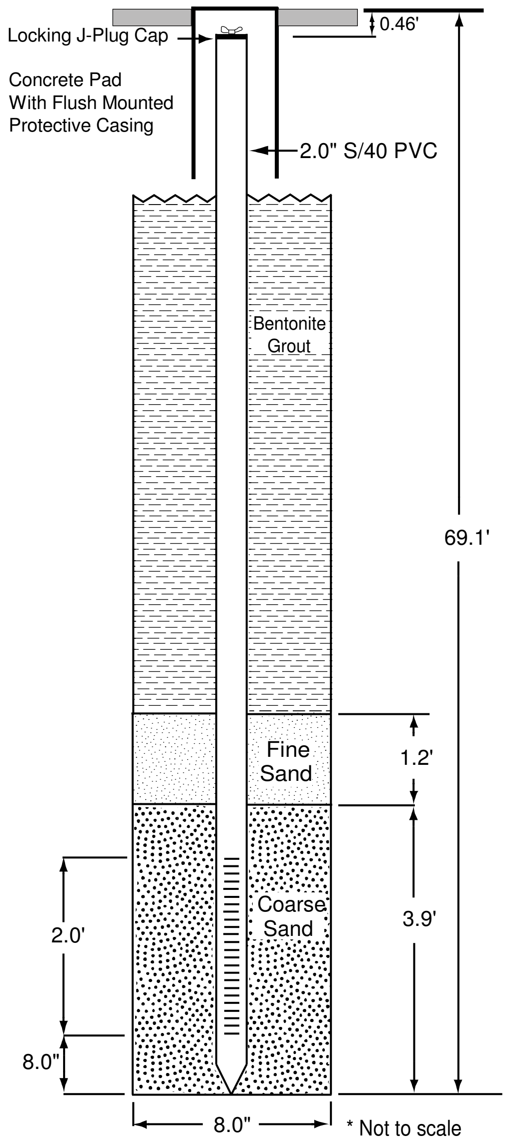
C-15 C-35 C-70 N

Ada Hayden Heritage Park Well C-70

Installation Date: 03/29/06
Total Depth: 69.1'
Drilling method: Auger

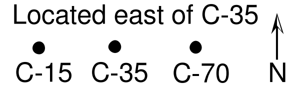
UTM Northing (NAD 83, Zone 15): 4657050.556640
UTM Easting (NAD 83, Zone 15): 447587.060854

Top of Casing: 908.281 ft
Screen Size: 0.020 slot



Notes:

Located east of C-35

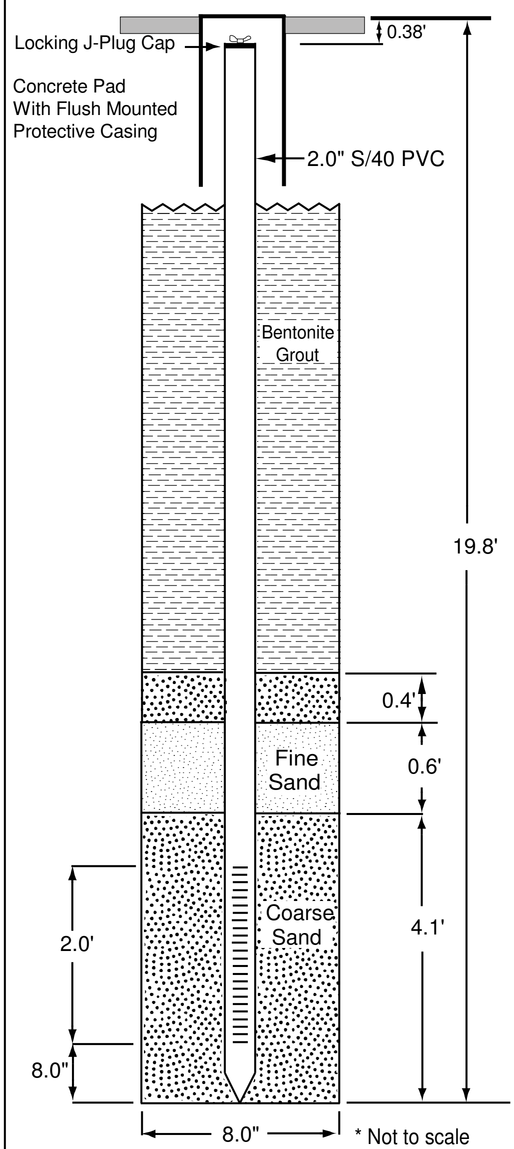


Ada Hayden Heritage Park Well
D-20

Installation Date: 03/30/06
Total Depth: 19.8'
Drilling method: Auger

UTM Northing (NAD 83, Zone 15): 4656854.796970
UTM Easting (NAD 83, Zone 15): 448342.278576

Top of Casing: 908.540 ft
Screen Size: 0.020 slot



* Not to scale

Notes:

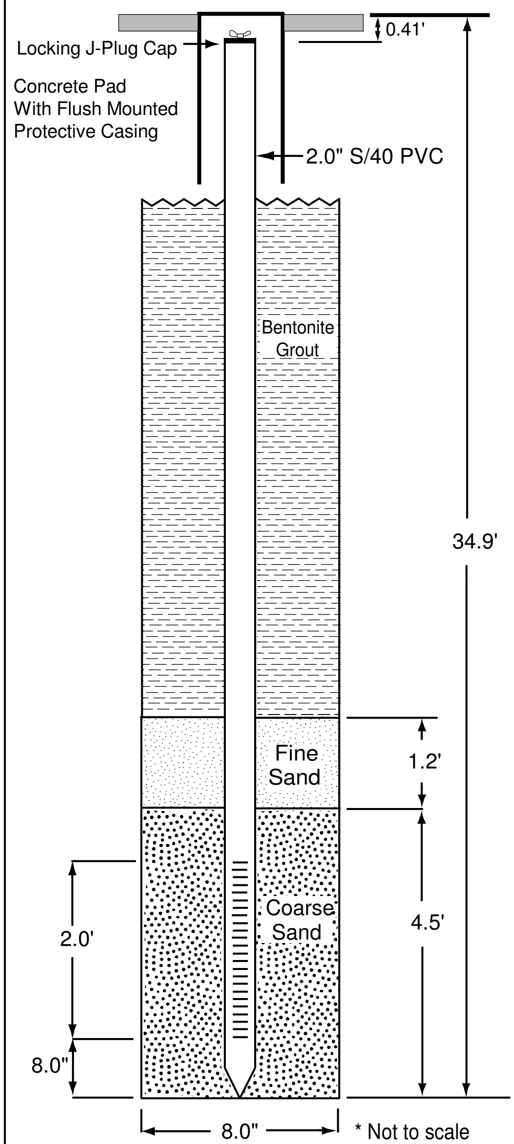
Located west of D-35

D-55 D-20 D-35 N

Put in more coarse sand on top of fine sand to hold it down when pumping in grout.

Ada Hayden Heritage Park Well
D-35

Installation Date: 03/30/06 | UTM Northing (NAD 83, Zone 15): 4656855.535670 | Top of Casing: 908.501 ft
Total Depth: 34.9' | UTM Easting (NAD 83, Zone 15): 448343.772834 | Screen Size: 0.020 slot
Drilling method: Auger



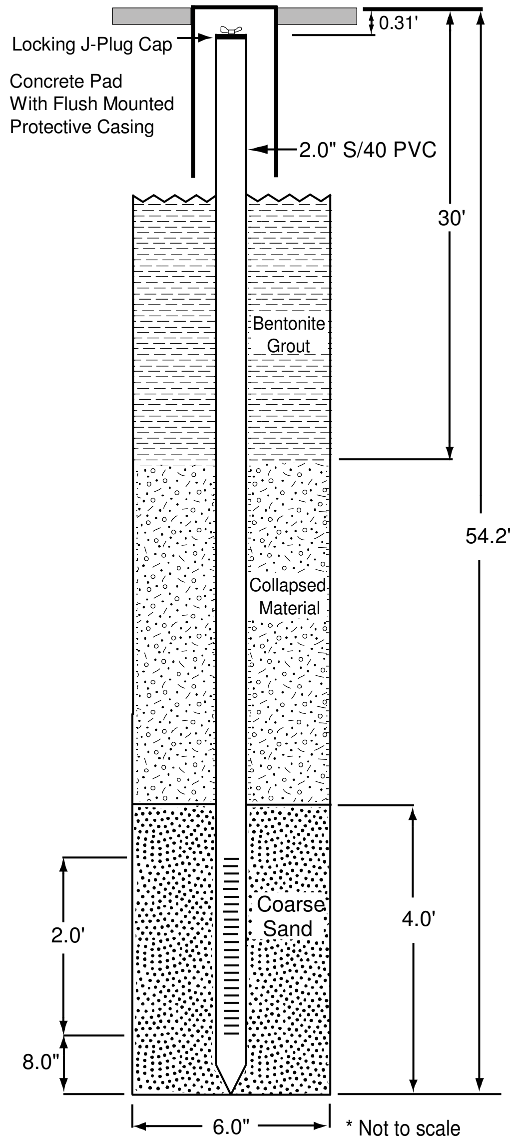
Notes:

Located east of D-20

D-55 D-20 D-35 N

Ada Hayden Heritage Park Well
D-55

Installation Date: 04/06/06 | UTM Northing (NAD 83, Zone 15): 4656853.844980 | Top of Casing: 908.922 ft
Total Depth: 54.2' | UTM Easting (NAD 83, Zone 15): 448340.521952 | Screen Size: 0.020 slot
Drilling method: Mud Rotary



* Not to scale

Notes:

Located west of D-20

D-55 D-20 D-35 N

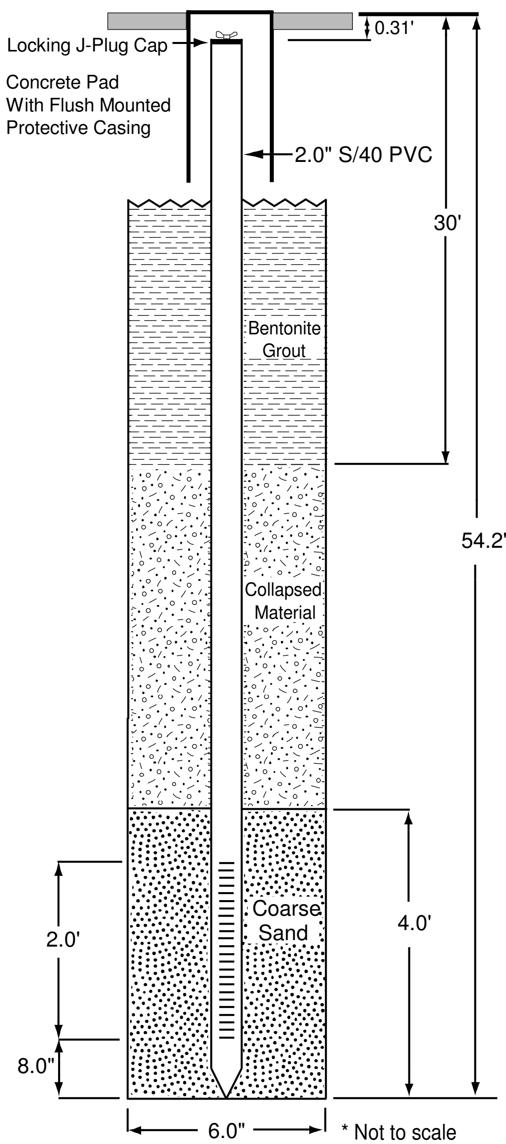
Hole collapsed when putting in coarse sand. Collapsed to ~30 ft from the ground surface. Unsuccessfully tried to jet out. Can not be sure about the effective screen length. A connection may exist with sand and gravel above.

Ada Hayden Heritage Park Well
D-55

Installation Date: 04/06/06 UTM Northing (NAD 83, Zone 15): 4656853.844980 Top of Casing: 908.922 ft

Total Depth: 54.2' UTM Easting (NAD 83, Zone 15): 448340.521952 Screen Size: 0.020 slot

Drilling method: Mud Rotary



* Not to scale

Notes:

Located west of D-20

D-55 D-20 D-35 N

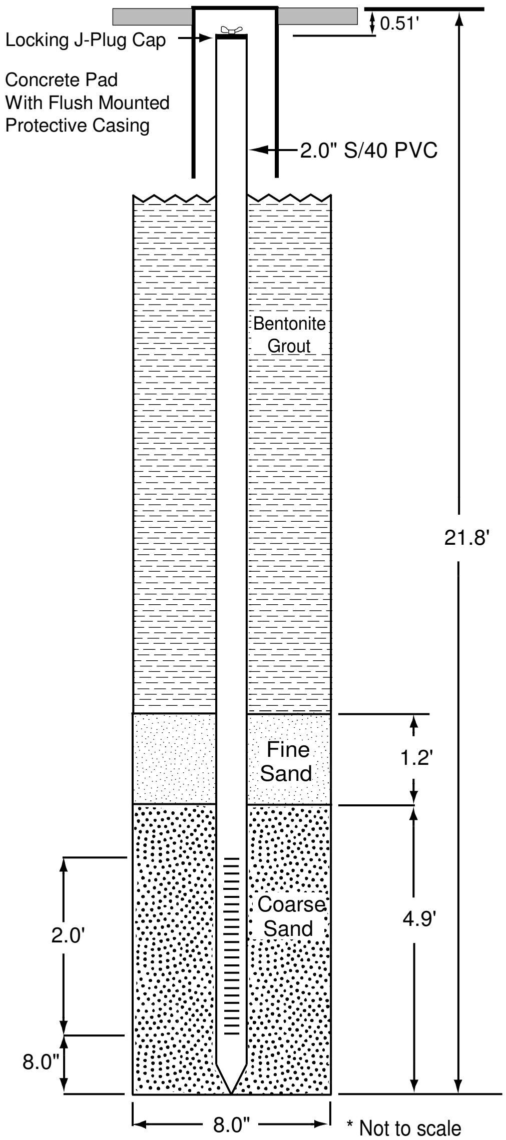
Hole collapsed when putting in coarse sand. Collapsed to ~30 ft from the ground surface. Unsuccessfully tried to jet out. Can not be sure about the effective screen length. A connection may exist with sand and gravel above.

Ada Hayden Heritage Park Well
E-22

Installation Date: 04/03/06 UTM Northing (NAD 83, Zone 15): 4657445.956650 Top of Casing: 907.050 ft

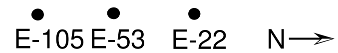
Total Depth: 21.8' UTM Easting (NAD 83, Zone 15): 448418.396019 Screen Size: 0.020 slot

Drilling method: Auger



Notes:

Located north of E-53

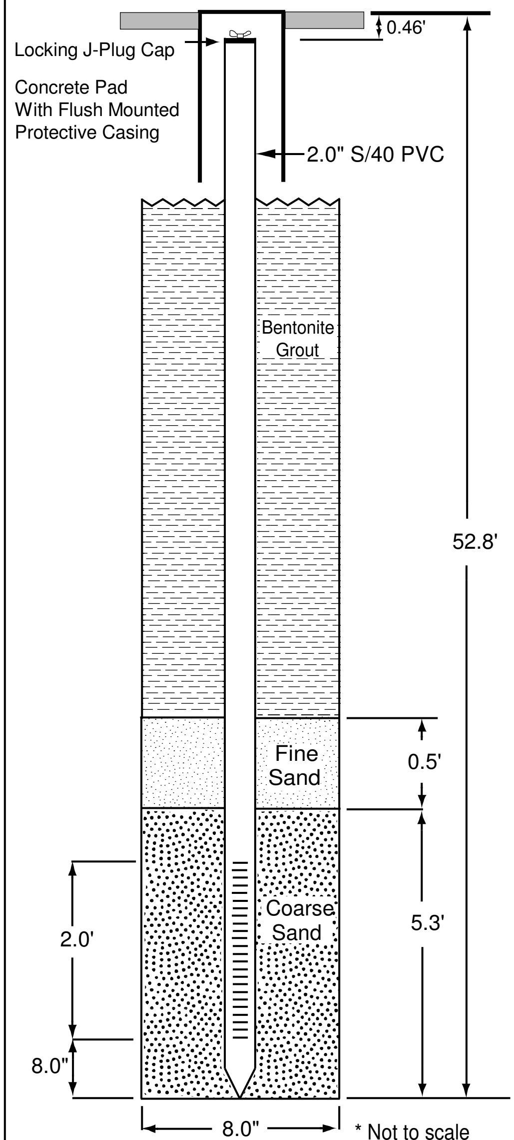


Ada Hayden Heritage Park Well
E-53

Installation Date: 03/31/06
Total Depth: 52.8'
Drilling method: Auger

UTM Northing (NAD 83, Zone 15): 4657444.136020
UTM Easting (NAD 83, Zone 15): 448418.149267

Top of Casing: 907.042 ft
Screen Size: 0.020 slot



* Not to scale

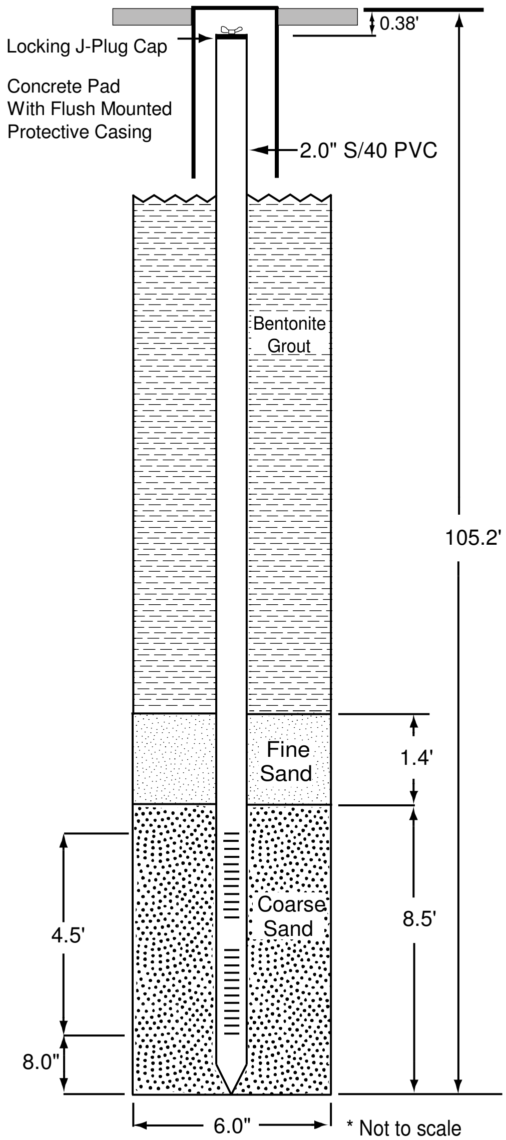
Notes:

Located north of E-105

E-105 E-53 E-22 N→

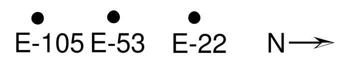
Ada Hayden Heritage Park Well
E-105

Installation Date: 04/13/06 UTM Northing (NAD 83, Zone 15): 4657441.481340 Top of Casing: 907.101 ft
Total Depth: 105.2' UTM Easting (NAD 83, Zone 15): 448417.762976 Screen Size: 0.020 slot
Drilling method: Mud Rotary



Notes:

Located south of E-53

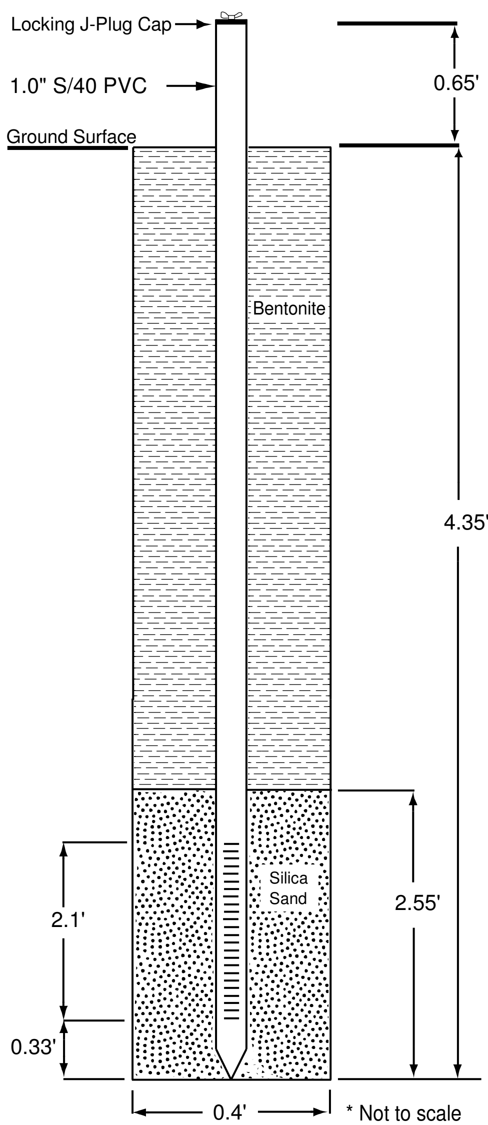


Ada Hayden Heritage Park Well
F-5

Installation Date: 8/4/2006
Total Depth: 4.35'
Drilling method: Hand auger

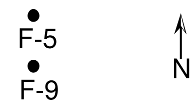
UTM Northing (NAD 83, Zone 15): 4657830.26
UTM Easting (NAD 83, Zone 15): 447760.19

Top of Casing: 902.31
Screen Size: 0.020 slot



Notes:

Located north of F9.

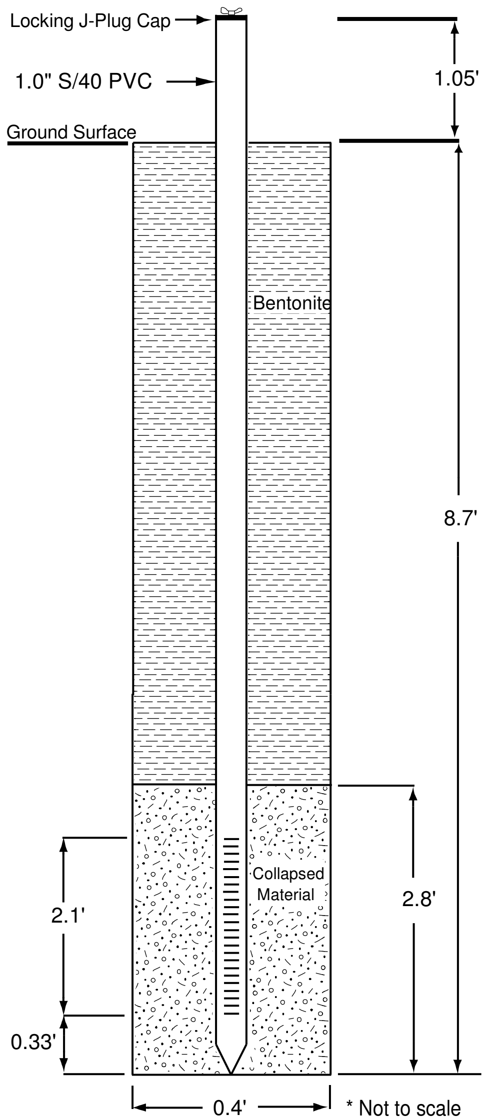


Ada Hayden Heritage Park Well
F-9

Installation Date: 8/4/2006
Total Depth: 8.7'
Drilling method: Hand auger

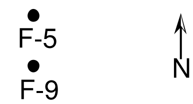
UTM Northing (NAD 83, Zone 15): 4657830.84
UTM Easting (NAD 83, Zone 15): 447759.92

Top of Casing: 902.707
Screen Size: 0.020 slot



Notes:

Located south of F5.



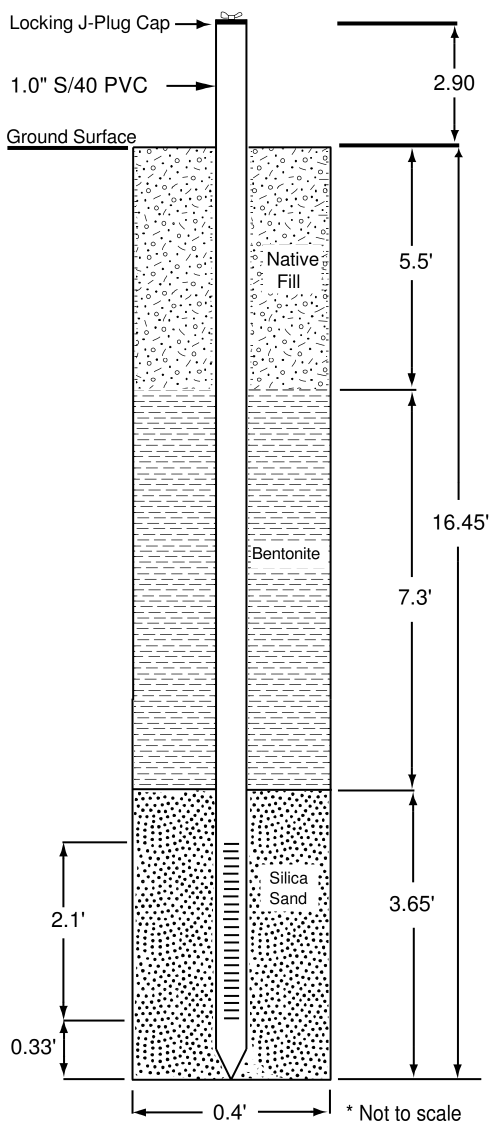
Ada Hayden Heritage Park Well
G-16

Installation Date: 8/5/2006
Total Depth: 16.45'
Drilling method: Hand auger

UTM Northing (NAD 83, Zone 15): 4657722.37
UTM Easting (NAD 83, Zone 15): 447197.27

Top of Casing: 913.654
Screen Size: 0.020 slot

Notes:

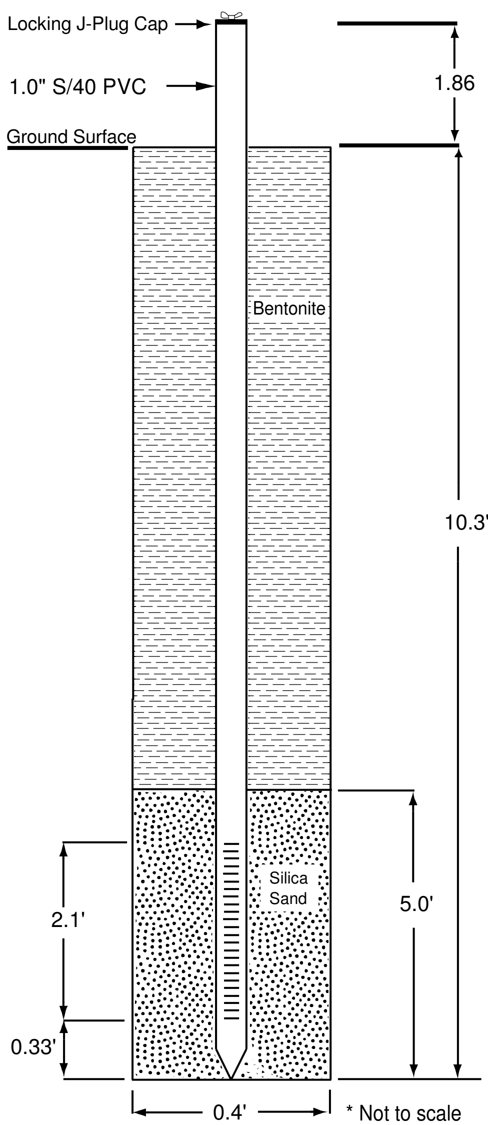


Ada Hayden Heritage Park Well
H-10

Installation Date: 8/7/2006
Total Depth: 10.3'
Drilling method: Hand auger

UTM Northing (NAD 83, Zone 15): 4657389.81
UTM Easting (NAD 83, Zone 15): 447348.32

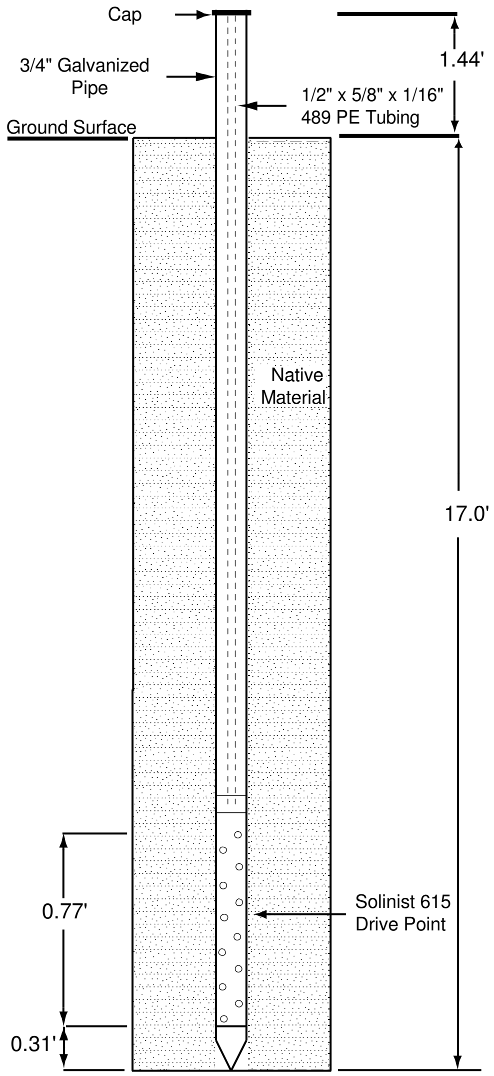
Top of Casing: 905.797
Screen Size: 0.020 slot



Notes:

Ada Hayden Heritage Park Well
I-17

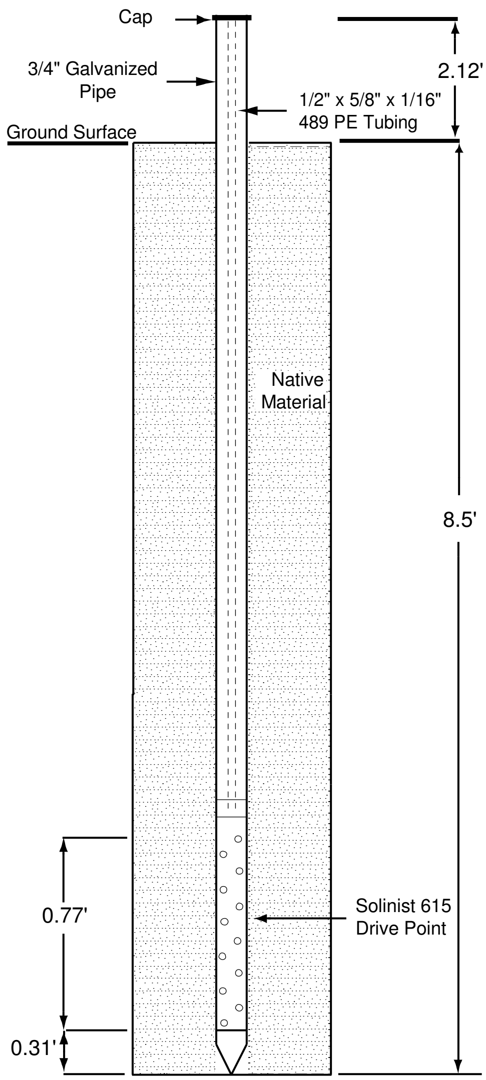
Installation Date: 10/20/2006 UTM Northing (NAD 83, Zone 15): 4657585.69 Top of Casing: 905.391
Total Depth: 17.0' UTM Easting (NAD 83, Zone 15): 447985.49 Drive Point: Solinist 615
Drilling method: Hand driven



Notes:

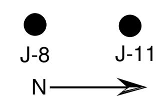
Ada Hayden Heritage Park Well
J-8.5

Installation Date: 11/01/2006
UTM Northing (NAD 83, Zone 15): 4657582.16
Top of Casing: 902.441
Total Depth: 8.5'
UTM Easting (NAD 83, Zone 15): 448519.77
Drive Point: Solinist 615
Drilling method: Hand driven



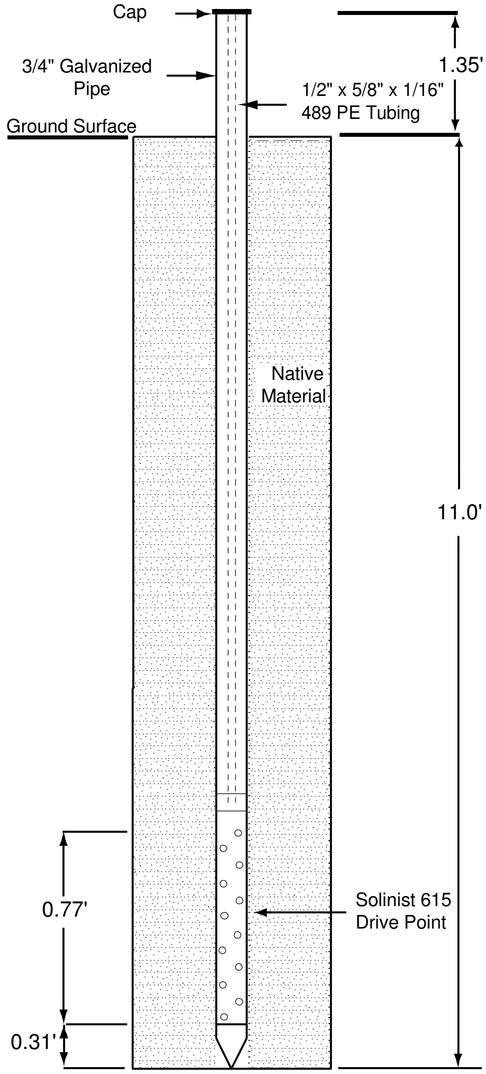
Notes:

Located south of J-11



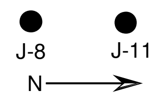
Ada Hayden Heritage Park Well J-11

Installation Date: 10/20/2006
UTM Northing (NAD 83, Zone 15): 4657582.80
Top of Casing: 901.552
Total Depth: 11.0'
UTM Easting (NAD 83, Zone 15): 448520.06
Drive Point: Solinist 615
Drilling method: Hand driven



Notes:

Located north of J-11



APPENDIX E

HEAD MEASUREMENTS

Table E 1. Hydraulic head measurements taken from April 18, 2006 to July 25, 2007.

Piezometer	4/18/2006	5/2/2006	5/8/2006	6/6/2006	6/21/2006	8/3/2006	8/30/2006	9/14/2006	9/25/2006	10/25/2006
A15	897.41	895.85	897.74	897.29	896.98	896.73	897.16	898.01	898.07	897.54
A35	897.45	896.89	897.85	897.16	897.19	896.92	897.32	898.22	898.26	897.81
A60	897.05	902.26	902.46	901.86	901.23	900.98	901.26	901.97	902.48	902.05
B13	897.97	899.02	899.02	897.40	896.98	896.70	897.31	899.11	899.35	898.22
B35	898.04	899.04	899.01	897.46	897.06	896.81	897.37	899.11	899.33	898.25
B64	897.90	898.59	898.54	897.55	897.13	896.82	897.35	898.68	898.85	898.03
B138	899.28	899.98	899.98	898.88	898.23	897.81	898.39	899.97	900.26	899.43
C15	897.28	897.68	897.58	897.10	896.79	896.57	897.03	897.71	897.99	897.39
C35	897.26	897.67	897.56	897.05	896.77	896.57	897.03	897.88	897.98	897.36
C70	897.26	897.67	897.54	897.05	896.76	896.56	897.03	897.85	897.97	897.35
D20	893.42	893.88	894.07	894.53	894.32	893.57	893.91	894.43	894.85	895.12
D35	892.71	893.36	893.38	892.68	892.18	891.47	891.79	893.75	893.79	892.89
D55	892.02	893.32	892.70	891.83	890.31	890.67	890.92	893.52	893.11	892.13
E22	894.65	895.64	895.19	894.48	894.10	893.63	893.88	896.41	895.59	894.67
E53	895.42	896.25	895.92	895.25	894.89	894.67	895.00	896.76	896.53	895.73
E105	891.97	893.19	892.68	890.83	891.30	890.66	890.87	893.75	893.13	892.17
F5	-	-	-	-	-	-	899.68	-	-	-
F9	-	-	-	-	-	-	900.35	-	-	-
G16	-	-	-	-	-	-	898.49	-	-	-
H10	-	-	-	-	-	-	898.62	-	-	-
I17	-	-	-	-	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	-	-	-	-
J11	-	-	-	-	-	-	-	-	-	-
Lake Level	-	-	-	897.02	896.78	896.60	896.87	897.69	897.83	897.23
S. Skunk River	-	-	-	-	-	891.81	891.94	894.62	893.44	892.74

Note: All values in ft above m.s.l. (mean sea level)
S. Skunk River value based off USGS gage station 05470000
Piezometers F5, F9, G16, H10, I17, J8.5 and J11 were installed August, 2006
Dashes indicate measurement not taken

Table E 1. (Continued)

Piezometer	10/29/2006	11/20/2006	12/20/2006	1/24/2007	2/21/2007	4/2/2007	5/30/2007	6/26/2007	7/25/2007
A15	-	897.28	897.47	898.06	896.66	899.53	899.45	898.06	897.24
A35	-	897.54	897.63	898.16	897.95	899.44	899.70	898.27	897.49
A60	-	900.91	902.09	900.74	902.18	903.72	904.01	903.06	901.95
B13	-	897.80	898.13	899.03	897.64	-	-	906.72	904.59
B35	-	897.85	898.17	899.03	898.18	-	-	906.58	904.55
B64	-	897.74	898.14	898.62	897.78	-	-	905.77	904.53
B138	-	899.16	899.47	900.27	899.26	-	-	907.78	906.06
C15	-	897.16	897.31	897.70	897.26	898.40	898.41	897.65	897.05
C35	-	897.14	897.28	897.73	897.26	898.38	898.30	897.66	897.02
C70	-	897.14	897.26	897.73	897.25	898.36	898.28	897.63	897.01
D20	-	894.64	894.65	895.02	894.55	895.63	896.32	895.67	894.89
D35	-	892.55	892.58	893.12	892.56	894.77	895.44	894.48	892.75
D55	-	891.76	891.70	892.18	891.67	894.21	894.41	893.71	891.45
E22	-	894.37	894.34	894.76	894.33	896.08	896.25	895.70	894.10
E53	-	886.42	895.41	895.94	895.52	897.09	897.13	896.49	895.26
E105	-	891.75	891.73	892.24	891.71	894.15	894.36	895.68	891.47
F5	900.10	899.12	899.74	-	-	-	-	-	898.20
F9	900.00	899.82	899.76	-	-	-	-	-	898.03
G16	900.18	900.12	900.73	903.12	913.65	906.74	907.82	905.51	902.64
H10	900.20	899.77	900.03	900.50	905.80	901.98	901.39	900.57	899.62
I17	-	897.51	896.48	897.95	896.75	901.84	898.73	898.03	896.88
J8.5	893.95	893.83	893.77	894.02	893.79	896.22	895.42	895.07	893.41
J11	894.08	893.97	893.76	894.05	893.86	896.28	895.49	895.16	893.41
Lake Level	-	897.02	897.14	-	-	897.98	897.96	897.43	896.94
S. Skunk River	-	892.61	892.52	892.78	892.50	894.57	893.86	893.79	892.28

Note: All values in ft above m.s.l. (mean sea level)
S. Skunk River value based off USGS gage station 05470000
Piezometers F5, F9, G16, H10, I17, J8.5 and J11 were installed August, 2006
Dashes indicate measurement not taken

APPENDIX F

MONTHLY WATER QUALITY ANALYSES

Table F1. Ammonia NH_3-N concentrations in mg/L.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A35	0.50	0.25	0.82	0.52	0.47	0.00	0.00	0.00	0.09	0.00	0.00	0.54	0.43
A60	1.94	1.55	2.06	2.05	2.04	2.08	2.00	1.68	1.66	0.84	1.24	1.55	2.12
B13	0.21	0.18	0.21	0.20	0.13	0.16	0.15	0.16	0.16	-	-	-	0.10
B35	1.52	1.36	1.55	1.41	1.35	1.34	1.37	1.47	1.49	-	-	-	1.06
B64	1.26	1.64	2.02	1.99	2.01	2.00	2.01	2.05	2.04	-	-	-	2.13
B138	0.84	0.74	0.81	0.67	0.82	0.18	0.08	0.00	0.64	-	-	-	0.81
C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
C35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
C70	0.34	0.37	0.39	0.42	0.48	0.49	0.46	0.05	0.53	0.00	0.47	0.41	0.44
D20	0.72	0.83	1.09	1.12	0.91	1.06	0.88	1.00	0.94	0.83	0.42	0.68	1.01
D35	0.73	0.72	0.78	0.78	0.81	0.82	0.78	0.60	0.77	0.00	0.00	0.65	0.82
D55	0.96	1.13	1.21	1.26	1.34	1.37	1.28	1.35	1.41	0.00	1.09	1.25	1.34
E22	0.19	0.21	0.22	0.22	0.22	0.21	0.20	0.22	0.21	0.16	0.18	0.20	0.23
E53	0.61	0.61	0.66	0.66	0.68	0.67	0.65	0.67	0.68	0.00	0.00	0.62	0.70
E105	0.75	0.80	0.89	0.82	0.92	0.91	0.89	0.91	0.17	0.00	0.00	0.71	0.94
F5	-	-	-	-	-	0.00	0.00	-	-	-	-	-	-
F9	-	-	-	-	-	2.00	0.61	-	-	-	-	-	-
G16	-	-	-	-	-	0.00	0.00	-	-	-	-	-	-
H10	-	-	-	-	-	0.00	0.00	-	-	-	-	-	-
I17	-	-	-	-	-	-	1.15	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	0.00	-	-	-	-	-	-
J11	-	-	-	-	-	-	0.00	-	-	-	-	-	-

Note: If 0.00 then the value is below the minimum detection limit (MDL) or practical quantitation limit (PQL).
Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.

Table F2. Total phosphorus concentrations in μg/L.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	82.63	27.98	28.37	14.59	26.91	13.07	26.31	43.07	19.02	413.80	23.11	17.41	40.22
A35	53.71	137.16	77.21	24.76	37.60	23.46	26.06	33.19	44.38	33.70	59.27	36.33	66.27
A60	365.02	127.99	311.44	369.06	315.14	419.01	362.74	408.00	396.76	112.83	297.12	394.49	509.01
B13	45.82	50.65	50.63	52.86	44.70	45.87	40.05	27.04	39.86	-	-	-	24.93
B35	292.30	333.44	293.27	267.91	248.26	257.95	224.43	280.72	252.87	-	-	-	239.84
B64	214.59	217.16	202.11	200.99	192.39	210.63	185.83	247.72	223.70	-	-	-	307.03
B138	15.64	23.51	18.56	20.98	9.21	0.00	0.00	17.37	20.32	-	-	-	10.89
C15	128.35	267.53	86.76	27.52	48.81	25.41	95.82	230.15	437.65	39.02	18.67	545.43	405.85
C35	0.00	8.84	9.50	0.00	0.00	0.00	0.00	8.52	8.90	0.00	23.77	8.41	8.08
C70	42.24	54.60	54.97	54.66	48.43	54.27	40.34	54.54	53.88	14.97	70.16	48.67	59.07
D20	467.45	355.96	527.53	189.59	500.51	417.57	334.83	441.88	348.03	187.98	321.65	564.46	97.73
D35	284.12	175.56	179.74	144.46	26.10	184.69	117.30	484.19	388.16	81.37	80.98	509.62	558.40
D55	75.70	105.16	65.90	43.98	9.13	52.63	42.45	55.09	60.82	10.74	60.31	71.45	58.62
E22	123.58	96.42	90.67	91.79	78.09	84.06	68.80	96.78	190.31	84.50	100.41	114.00	92.27
E53	53.35	49.09	33.03	29.99	10.91	83.80	25.80	48.14	39.64	0.00	17.57	42.10	33.95
E105	33.78	68.46	43.45	38.39	31.67	44.19	35.55	48.04	59.28	106.03	106.81	64.99	47.87
F5	-	-	-	-	-	146.25	141.70	-	-	-	-	-	-
F9	-	-	-	-	-	296.16	172.87	-	-	-	-	-	-
G16	-	-	-	-	-	18.95	94.23	-	-	-	-	-	-
H10	-	-	-	-	-	20.65	14.77	-	-	-	-	-	-
I17	-	-	-	-	-	-	96.80	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	33.78	-	-	-	-	-	-
J11	-	-	-	-	-	-	35.23	-	-	-	-	-	-

Note: If 0.00 then the value is below the minimum detection limit (MDL) or practical quantitation limit (PQL).
Wells at nest B flooded on 4/2/2007,4/24/2007,5/30/2007.
Dashes indicate no sample taken.

Table F3. Soluble reactive phosphorus (SRP) concentrations in μg/L.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	0.00	0.00	8.90	10.86	12.30	11.79	11.98	13.78	9.21	12.83	12.48	12.94	6.34
A35	0.00	21.74	18.05	16.26	21.20	17.80	16.24	14.69	14.03	11.05	12.15	19.47	12.15
A60	0.00	39.58	286.09	395.68	317.27	417.91	363.00	332.47	325.71	20.47	370.00	365.44	437.12
B13	0.00	38.79	41.25	49.95	44.18	43.97	30.09	21.18	19.73	-	-	-	12.37
B35	0.00	304.50	304.93	283.02	228.03	251.46	223.88	279.44	224.85	-	-	-	227.26
B64	0.00	198.63	202.30	200.97	183.38	204.91	171.97	240.51	216.36	-	-	-	264.32
B138	0.00	16.03	6.57	15.63	7.75	0.00	0.00	5.72	0.00	-	-	-	0.00
C15	0.00	12.77	0.00	23.67	21.38	20.03	15.52	30.94	10.11	14.96	9.38	15.95	6.78
C35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.27	0.00	5.08	0.00	6.53	0.00
C70	0.00	43.73	38.64	50.93	49.91	52.79	44.01	57.17	48.54	5.76	46.78	49.23	51.82
D20	0.00	493.59	361.73	407.73	548.30	522.82	296.44	592.63	309.39	359.23	498.22	603.18	593.04
D35	0.00	9.87	133.84	141.52	110.34	175.93	191.44	154.45	233.30	99.81	41.69	126.99	176.61
D55	0.00	52.91	40.24	36.06	50.03	44.26	34.33	47.63	47.67	8.10	50.93	69.33	58.90
E22	0.00	80.32	75.00	90.50	76.55	78.16	65.45	87.70	81.15	81.69	81.61	93.38	86.20
E53	0.00	15.47	0.00	20.87	20.83	23.77	18.98	27.36	23.16	5.02	0.00	26.56	19.96
E105	0.00	27.83	21.83	34.41	34.94	38.71	33.37	39.63	25.92	80.89	90.58	48.24	38.63
F5	-	-	-	-	-	107.76	118.29	-	-	-	-	-	-
F9	-	-	-	-	-	225.07	395.27	-	-	-	-	-	-
G16	-	-	-	-	-	16.10	6.05	-	-	-	-	-	-
H10	-	-	-	-	-	18.36	10.40	-	-	-	-	-	-
I17	-	-	-	-	-	-	0.00	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	11.47	-	-	-	-	-	-
J11	-	-	-	-	-	-	22.06	-	-	-	-	-	-

Note: If 0.00 then the value is below the minimum detection limit (MDL) or practical quantitation limit (PQL).
Starting on 8/3/2006 effort was made to get samples to the lab faster and also samples were collected in glass bottles.
Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.

Table F4. Nitrate-N concentrations in mg/L.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	8.28	7.64	9.52	8.92	9.26	9.20	8.20	7.86	5.86	7.11	3.04	1.12	2.15
A35	0.00	0.00	0.00	0.00	0.00	0.97	1.28	0.74	0.84	0.71	0.91	0.00	0.00
A60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-	0.00
B35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-	0.00
B64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-	0.00
B138	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.00	-	-	-	0.00
C15	2.21	2.13	2.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C35	5.63	5.45	4.84	2.95	2.69	2.10	1.21	0.71	0.63	0.00	0.00	0.00	0.00
C70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.00	0.00	0.00
D20	0.00	3.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.41	0.00	0.00	0.00
D35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00
D55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	0.00	0.00
E22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.72	0.79	0.00	0.00
E105	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00
F5	-	-	-	-	-	0.00	0.00	-	-	-	-	-	-
F9	-	-	-	-	-	0.00	0.00	-	-	-	-	-	-
G16	-	-	-	-	-	2.18	2.15	-	-	-	-	-	-
H10	-	-	-	-	-	0.00	1.16	-	-	-	-	-	-
I17	-	-	-	-	-	-	0.00	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	3.96	-	-	-	-	-	-
J11	-	-	-	-	-	-	0.00	-	-	-	-	-	-

Note: If 0.00 then the value is below the minimum detection limit (MDL) or practical quantitation limit (PQL).
Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.

Table F5. pH.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	7.31	7.36	7.53	7.55	7.63	7.49	7.32	7.40	7.43	7.46	7.43	7.48	7.58
A35	7.45	7.42	7.50	7.70	7.65	7.67	7.77	7.62	7.62	7.60	7.59	7.47	7.64
A60	7.83	7.67	7.76	7.73	7.80	7.64	7.64	7.58	7.75	7.78	7.74	7.77	7.78
B13	7.57	7.72	7.46	7.45	7.58	7.49	7.49	7.58	7.62	-	-	-	7.65
B35	7.72	7.51	7.58	7.61	7.68	7.54	7.76	7.59	7.75	-	-	-	7.50
B64	7.99	7.67	7.74	7.78	7.76	7.75	7.79	7.74	7.77	-	-	-	7.79
B138	7.55	7.46	7.54	7.52	7.49	7.49	7.49	7.45	7.72	-	-	-	7.59
C15	7.05	6.84	7.23	6.78	6.80	6.70	6.81	6.78	6.91	6.82	6.89	6.85	6.90
C35	7.54	7.65	7.65	7.78	7.64	7.50	7.66	7.60	7.71	7.70	7.69	7.65	7.69
C70	7.71	7.56	7.58	7.73	7.58	7.57	7.55	7.41	7.65	7.63	7.53	7.58	7.66
D20	7.33	6.98	6.97	7.00	7.06	6.94	7.02	7.26	7.09	7.00	7.07	6.99	7.40
D35	7.42	7.41	7.25	7.27	7.26	7.14	7.26	7.20	7.41	7.68	7.60	7.31	7.07
D55	7.94	7.54	7.69	7.69	7.75	7.60	7.66	7.73	7.76	7.85	7.61	7.62	7.25
E22	7.77	7.56	7.62	7.64	7.71	7.63	7.63	7.55	7.76	7.60	7.59	7.67	7.60
E53	7.85	7.43	7.66	7.70	7.78	7.52	7.88	7.58	7.71	7.76	7.71	7.72	7.61
E105	7.82	7.64	7.75	7.80	7.73	7.66	7.92	7.65	7.85	8.30	8.20	7.71	7.66
F5	-	-	-	-	-	7.04	7.15	-	-	-	-	-	-
F9	-	-	-	-	-	6.74	6.90	-	-	-	-	-	-
G16	-	-	-	-	-	7.56	7.74	-	-	-	-	-	-
H10	-	-	-	-	-	7.22	7.23	-	-	-	-	-	-
I17	-	-	-	-	-	-	8.27	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	7.52	-	-	-	-	-	-
J11	-	-	-	-	-	-	7.76	-	-	-	-	-	-

Note: Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dasheds indicate no sample taken.

Table F6. Alkalinity (as mg/L $CaCO_3$).

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	305.5	308.0	303.0	301.5	308.0	306.5	306.5	308.0	314.5	288.0	310.0	295.9	276.0
A35	453.0	440.0	456.0	437.0	439.0	436.0	433.0	443.0	414.0	432.0	451.0	458.1	440.0
A60	468.5	461.0	459.0	454.0	462.5	458.5	460.5	461.5	461.5	398.0	444.0	454.9	463.5
B13	253.5	242.0	249.0	256.0	258.0	266.0	262.5	286.0	297.3	-	-	-	185.5
B35	369.0	373.0	375.0	318.5	318.0	312.0	351.5	335.5	329.0	-	-	-	282.0
B64	414.5	399.0	401.0	399.0	402.0	399.5	406.0	413.0	408.0	-	-	-	388.0
B138	411.5	394.0	405.0	392.0	409.0	394.8	402.5	404.0	399.0	-	-	-	410.0
C15	421.5	403.0	396.5	490.0	489.0	477.5	497.0	493.0	486.0	482.8	507.5	531.8	498.0
C35	232.0	226.0	230.0	233.0	241.0	238.0	246.5	249.0	248.0	235.5	259.0	243.8	239.0
C70	261.0	252.0	255.5	275.0	305.0	292.3	280.0	296.0	286.5	196.3	264.0	261.9	263.5
D20	646.0	622.5	563.0	577.5	556.0	582.5	500.0	515.0	523.5	462.0	351.0	580.1	408.0
D35	792.0	1175.0	1210.0	1311.0	784.0	445.0	672.0	441.0	337.0	252.5	235.0	598.0	505.0
D55	232.0	226.0	235.0	252.0	279.0	274.0	365.0	275.0	296.0	230.5	290.5	296.8	263.0
E22	240.0	227.5	225.0	219.0	229.0	223.5	226.0	226.0	228.0	227.0	243.0	238.2	232.0
E53	292.0	285.0	286.0	327.0	311.0	288.0	296.0	289.5	288.0	271.0	276.5	304.0	290.5
E105	347.5	347.0	346.0	337.0	345.5	338.5	353.0	341.5	183.0	73.0	77.5	316.2	346.5
F5	-	-	-	-	-	398.5	413.0	-	-	-	-	-	-
F9	-	-	-	-	-	560.0	292.0	-	-	-	-	-	-
G16	-	-	-	-	-	278.0	315.0	-	-	-	-	-	-
H10	-	-	-	-	-	351.0	356.0	-	-	-	-	-	-
I17	-	-	-	-	-	-	723.0	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	354.0	-	-	-	-	-	-
J11	-	-	-	-	-	-	650.0	-	-	-	-	-	-

Note: Samples from site D often show very high alkalinity. On 12/20/2006 sample were also run filtered. For consistency the non-filtered Data are presented in the table. Filtered values were: D20 = 499, D35 = 340, D55 = 271. On 1/24/2007 D35 was run filtered with a result of 286.5.
Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.

Table F7. Total carbon concentrations in mg/L.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	74.20	73.97	77.69	78.48	74.10	75.34	74.87	74.46	77.00	71.77	55.12	69.76	70.26
A35	108.90	106.45	111.35	106.30	107.15	105.00	105.60	108.00	108.50	107.65	78.83	111.30	109.65
A60	108.85	110.65	113.60	111.55	109.55	111.70	110.30	111.45	111.75	97.72	70.21	109.75	113.00
B13	62.25	60.66	64.31	65.72	64.03	68.11	66.46	71.25	73.83	-	-	-	48.46
B35	86.48	89.80	93.98	79.21	77.39	78.41	85.91	83.58	82.12	-	-	-	73.67
B64	93.51	95.02	98.42	95.90	94.11	95.88	96.76	99.06	97.87	-	-	-	94.89
B138	96.51	97.04	101.40	95.87	97.22	97.47	98.11	98.03	98.74	-	-	-	101.45
C15	127.65	403.00	116.60	140.55	134.10	129.55	158.30	142.05	138.85	148.15	58.05	158.30	158.90
C35	53.95	226.00	56.99	57.42	57.52	58.07	59.47	60.83	59.80	58.13	43.64	59.95	58.76
C70	60.98	60.39	63.14	66.68	72.99	70.56	69.94	71.18	70.12	49.53	44.38	63.02	66.21
D20	169.95	100.42	172.20	160.85	146.75	156.00	140.75	126.45	135.30	129.80	70.14	162.75	82.52
D35	85.07	62.31	70.43	77.66	83.86	86.16	87.65	74.01	89.36	65.86	55.19	81.56	146.95
D55	53.24	56.00	58.31	60.21	65.94	68.00	64.06	67.74	72.91	57.58	48.26	71.70	69.31
E22	55.37	55.81	56.38	53.93	54.53	55.54	54.46	55.22	56.24	56.65	44.57	57.37	55.30
E53	64.93	67.79	69.37	67.98	67.15	68.72	67.89	68.08	69.21	66.65	48.25	70.51	71.12
E105	81.39	83.49	83.40	81.21	80.52	82.19	81.18	81.05	39.98	18.18	18.67	73.70	84.25
F5	-	-	-	-	-	103.00	110.30	-	-	-	-	-	-
F9	-	-	-	-	-	74.18	81.16	-	-	-	-	-	-
G16	-	-	-	-	-	278.00	63.90	-	-	-	-	-	-
H10	-	-	-	-	-	351.00	87.64	-	-	-	-	-	-
I17	-	-	-	-	-	-	59.10	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	79.18	-	-	-	-	-	-
J11	-	-	-	-	-	-	74.87	-	-	-	-	-	-

Note: If 0.00 then the value is below the minimum detection limit (MDL) or practical quantitation limit (PQL).
Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.

Table F8. Total organic carbon concentrations in mg/L.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	1.82	1.29	1.47	1.26	1.27	1.45	1.24	1.31	1.45	1.41	0.35	1.47	32.61
A35	5.65	4.96	4.66	5.07	4.17	4.40	4.75	4.32	4.48	4.41	0.31	5.12	4.61
A60	3.48	3.51	3.29	3.34	3.27	3.21	3.12	3.26	3.20	3.83	0.39	3.46	3.22
B13	2.70	2.64	2.55	2.86	2.76	2.94	2.56	2.08	2.13	-	-	-	3.57
B35	3.38	3.49	3.07	2.91	2.94	2.86	3.00	3.14	3.12	-	-	-	2.74
B64	2.46	2.43	2.39	2.38	2.28	2.52	2.26	2.79	2.39	-	-	-	2.65
B138	1.93	1.52	1.39	1.85	1.19	1.28	1.15	1.26	1.21	-	-	-	1.18
C15	2.42	2.57	2.70	2.25	1.90	1.87	1.94	1.91	1.63	2.01	0.41	2.84	2.50
C35	1.20	1.26	0.97	1.07	1.16	1.04	1.05	1.37	0.92	1.15	0.36	1.13	1.06
C70	1.72	1.78	1.59	1.63	1.41	1.57	1.47	1.47	1.39	1.73	0.34	1.68	1.84
D20	6.90	6.16	6.57	6.59	5.99	6.54	6.18	6.90	5.66	5.50	0.41	6.83	3.45
D35	4.07	3.61	3.37	3.44	3.68	3.67	3.65	3.87	3.70	4.92	0.36	4.17	6.93
D55	2.54	2.81	2.49	2.37	2.55	2.75	1.44	2.58	2.50	2.58	0.34	2.64	2.57
E22	1.85	2.18	2.02	1.96	1.95	2.01	1.83	2.08	1.89	1.91	0.36	1.96	1.96
E53	1.65	2.01	1.84	1.74	1.72	1.80	1.66	1.84	1.66	1.91	0.36	1.81	1.86
E105	2.04	2.34	1.71	2.02	1.76	1.89	1.64	1.77	3.17	2.83	0.38	1.86	1.73
F5	-	-	-	-	-	4.65	4.47	-	-	-	-	-	-
F9	-	-	-	-	-	7.68	4.51	-	-	-	-	-	-
G16	-	-	-	-	-	1.02	0.85	-	-	-	-	-	-
H10	-	-	-	-	-	2.19	1.69	-	-	-	-	-	-
I17	-	-	-	-	-	-	3.94	-	-	-	-	-	-
J8.5	-	-	-	-	-	-	1.29	-	-	-	-	-	-
J11	-	-	-	-	-	-	1.24	-	-	-	-	-	-

Note: Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.

Table F9. Specific conductance (adjusted to 25 Cº) in µS.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	332.4	351.3	291.1	293.5	258.4	181.5	228.1	247.7	249.0	246.8	302.4	392.0	330.9
A35	365.9	374.4	285.5	298.4	296.7	237.0	285.2	260.1	273.7	285.9	322.9	432.1	350.0
A60	374.8	371.2	292.2	300.4	201.4	243.0	223.7	278.3	236.3	268.9	327.0	447.0	354.3
B13	316.0	310.5	267.6	265.1	270.0	240.6	275.2	233.1	241.5	-	-	-	288.3
B35	351.9	337.0	278.6	280.2	278.2	240.7	280.2	255.8	275.9	-	-	-	285.8
B64	339.7	329.2	257.1	261.1	278.4	235.0	287.4	272.1	260.1	-	-	-	317.8
B138	397.8	369.4	308.8	307.2	339.9	277.0	317.0	279.8	287.5	-	-	-	355.7
C15	591.0	497.9	247.9	381.5	537.0	413.0	464.9	-	369.9	432.6	475.8	607.0	609.0
C35	357.0	290.7	247.4	263.0	289.0	252.6	242.1	-	206.8	220.2	246.3	267.9	234.2
C70	269.7	285.2	177.4	260.3	306.7	295.5	321.9	-	351.1	286.9	307.9	325.1	292.8
D20	520.0	422.0	286.5	406.8	372.8	333.4	392.4	-	330.2	283.9	294.1	364.9	381.2
D35	354.0	280.1	273.3	282.1	290.0	273.4	266.0	-	293.0	203.3	281.5	296.6	298.0
D55	298.8	255.0	226.1	234.2	244.8	220.3	267.0	-	240.9	233.9	220.1	286.0	279.6
E22	282.6	257.6	233.1	230.0	244.8	220.0	235.0	171.1	225.6	229.5	229.3	292.4	253.4
E53	314.1	294.6	244.1	248.0	258.0	228.9	258.7	180.1	246.8	252.8	249.3	317.7	282.3
E105	346.9	328.1	261.5	275.0	279.2	247.1	280.7	185.1	244.2	109.7	110.8	289.9	299.4
F5	-	-	-	-	-	-	-	-	-	-	-	-	-
F9	-	-	-	-	-	-	-	-	-	-	-	-	-
G16	-	-	-	-	-	-	247.3	-	-	-	-	-	-
H10	-	-	-	-	-	-	309.3	-	-	-	-	-	-

Note: Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.

Table F10. Electrical conductivity in μS.

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	253.4	349.7	226.0	232.1	204.1	151.9	290.4	179.5	179.7	171.9	210.9	274.5	238.4
A35	280.7	285.5	215.4	220.6	226.8	180.0	213.4	188.1	201.8	203.8	235.3	313.8	262.8
A60	284.7	279.6	216.9	220.0	223.8	180.3	222.8	206.1	172.8	193.6	239.4	328.0	261.0
B13	250.0	245.8	216.8	212.4	225.4	193.5	217.2	145.1	149.2	-	-	-	268.5
B35	269.8	251.5	207.1	207.0	207.5	180.1	211.6	185.4	201.9	-	-	-	198.9
B64	253.2	240.7	188.6	191.6	203.2	172.6	208.1	201.3	185.9	-	-	-	229.1
B138	299.5	277.2	227.7	225.0	272.4	210.4	240.0	202.4	205.3	-	-	-	265.9
C15	451.0	404.0	263.8	301.8	427.5	316.9	356.9	-	252.8	296.1	318.2	441.9	472.0
C35	274.9	215.4	182.5	192.3	213.2	185.7	178.5	-	152.7	160.0	178.5	270.0	172.5
C70	364.5	209.8	242.0	190.1	223.5	213.9	233.9	-	254.1	209.5	222.7	237.7	213.4
D20	395.5	318.0	382.0	304.4	259.3	255.5	299.8	-	241.6	206.8	214.1	270.2	284.1
D35	272.0	219.5	203.4	207.9	216.0	202.8	201.1	-	218.7	148.6	207.2	217.8	220.0
D55	219.2	190.6	167.1	173.8	181.5	162.5	194.4	-	178.3	174.2	168.7	210.4	207.0
E22	223.5	202.7	184.6	180.6	195.0	175.2	185.3	171.1	172.1	173.4	170.8	222.0	193.4
E53	243.3	225.6	186.6	189.1	197.0	174.2	196.4	180.1	186.2	192.7	187.9	240.0	214.6
E105	265.0	248.0	197.4	210.1	212.0	185.4	210.2	185.1	183.0	83.2	83.6	212.8	221.5
F5	-	-	-	-	-	-	-	-	-	-	-	-	-
F9	-	-	-	-	-	-	-	-	-	-	-	-	-
G16	-	-	-	-	-	-	188.2	-	-	-	-	-	-
H10	-	-	-	-	-	-	233.9	-	-	-	-	-	-

Note: Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.

Table F11. Dissolved O_2 concentrations in mg/L.

Piezo.	8/3 2006	8/30	9/20	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	6/26
A15	5.3	6.8	5.6	5.5	7.0	6.5	5.9	5.7	11.0	7.3	7.7
A35	<2.0	<2.0	0.3	<2.0	4.8	<2.0	2.7	<2.0	2.1	<2.0	2.8
A60	3.9	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
B13	<2.0	<2.0	<2.0	<2.0	2.6	<2.0	<2.0	<2.0	-	-	<2.0
B35	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	-	-	<2.0
B64	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	-	-	<2.0
B138	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	-	-	<2.0
C15	4.5	2.3	3.7	4.6	8.4	2.6	<2.0	7.7	<2.0	<2.0	3.8
C35	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
C70	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
D20	5.4	8.9	<2.0	6.8	-	<2.0	<2.0	<2.0	<2.0	2.5	6.7
D35	8.7	<2.0	<2.0	13.8	11.7	<2.0	<2.0	5.6	<2.0	8.9	5.5
D55	<2.0	<2.0	<2.0	5.1	5.3	<2.0	<2.0	3.4	<2.0	2.8	<2.0
E22	<2.0	<2.0	<2.0	<2.0	3.4	<2.0	2.0	2.8	<2.0	<2.0	<2.0
E53	<2.0	<2.0	<2.0	<2.0	3.2	<2.0	2.3	<2.0	<2.0	<2.0	<2.0
E105	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
F5	-	-	-	-	>15.0	<2.0	-	-	-	-	-
F9	-	-	-	-	>15.0	<2.0	-	-	-	-	-
G16	-	-	-	-	3.0	4.8	-	-	-	-	-
H10	-	-	-	-	<2.0	-	-	-	-	-	-
I17	-	-	-	-		<2.0	-	-	-	-	-
J8.5	-	-	-	-		<2.0	-	-	-	-	-
J11	-	-	-	-		6.5	-	-	-	-	-

Note: Wells D55, D35, D20, F5, F9, J8.5 and J11 are often very cloudy so values or probably too high due to error in Chemetrics.
Data from 9/20/2006 was obtained with Hach Digital Titration kit.
Dashes indicate no sample taken.

Table F14. Temperature (^{o}C)

Piezo.	6/21 2006	8/3	8/30	9/25	10/25	11/20	12/20	1/24 2007	2/21	4/2	4/24	5/30	6/26
A15	12.6	12.9	13.3	14.0	13.9	13.5	-	10.4	9.1	9.4	9.4	10.2	11.1
A35	12.9	12.6	11.9	12.7	12.6	11.6	11.1	11.0	10.0	11.0	10.7	10.9	11.0
A60	12.4	12.0	11.6	11.5	11.4	11.5	11.2	11.0	10.4	11.1	11.2	11.2	11.0
B13	14.0	13.9	15.1	16.4	14.8	13.9	5.3	5.0	-	-	-	21.3	20.4
B35	12.7	11.7	11.7	11.7	11.7	12.0.	10.5	11.0	-	-	-	9.1	10.0
B64	11.7	10.9	10.9	10.8	11.2	10.7	11.5	10.0	-	-	-	10.4	10.2
B138	12.2	12.0	12.4	14.6	12.0	12.2	10.2	10.1	-	-	-	10.9	10.7
C15	12.6	15.1	12.8	14.7	14.1	13.2	-	9.3	8.5	8.8	10.8	12.4	12.8
C35	12.9	11.4	11.4	11.3	11.2	11.3	-	11.4	10.7	10.9	11.1	11	10.9
C70	11.5	11.1	11.0	10.9	10.8	10.8	-	10.7	10.9	10.6	10.8	10.8	10.7
D20	12.7	15.1	11.9	12.9	12.0	12.7	-	10.8	10.2	10.2	11.3	11.8	12.2
D35	12.9	12.9	11.5	11.5	11.4	11.7	-	11.7	11	11.2	11.1	11.3	11.5
D55	12.2	11.8	11.5	11.4	11.3	11.4	-	11.4	11.6	11.2	11.1	11.3	11.9
E22	14.1	13.9	14.2	14.3	14.3	14.0	12.9	12.6	12.2	11.7	12.2	12.5	12.8
E53	13.2	12.7	12.7	12.7	12.6	12.5	12.1	12.1	12.6	12	12.2	12.4	12.2
E105	12.6	12.3	12.1	12.3	11.9	12	11.7	11.8	12.4	12.2	11.4	11.3	11.4
F5	-	-	-	-	-	-	-	-	-	-	-	-	-
F9	-	-	-	-	-	-	-	-	-	-	-	-	-
G16	-	-	-	-	-	12.5	-	-	-	-	-	-	-
H10	-	-	-	-	-	12.4	-	-	-	-	-	-	-

Note: Wells at nest B flooded on 4/2/2007, 4/24/2007, 5/30/2007.
Dashes indicate no sample taken.